Gold King Mine Release – Analysis of Fate and Transport in the Animas and San Juan Rivers

Session 2: GKM Plume Travel and Water Quality

Gold King Mine Release Team
National Exposure Research Lab/ORD

June 22, 2016

GKM Plume Movement Through the River System

- How did the plume move?
- How was water quality affected?
- What was potential exposure?

The GKM Plume traveled as a coherent mass with beginning and end that could be observed and measured throughout the Animas River and through a portion of the San Juan River

Outline—Session 2

- Methods for quantifying metal mass in the GKM plume
- Plume characteristics and travel time
- Water quality characteristics during plume travel
- Geochemical reactions and transformations
- Exposure potential associated with metals concentrations

ORD Project Team

Team of ORD scientists with multidisciplinary expertise in geochemistry, surface and groundwater hydrology, environmental engineering, water quality modeling, fish biology and bioaccumulation, statistics, and geographical information tools

Asked by ORD Assistant Administrator to analyze fate and transport of GKM release

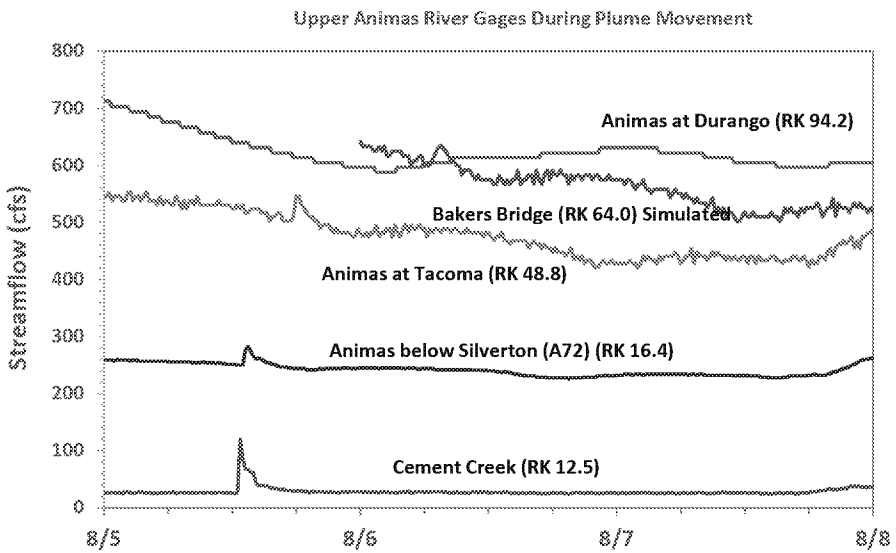
ORD/NERL Subject Experts Working on the Project

- **John Washington, Geochemistry**
- **Chris Knightes, WASP, water quality**
- **Mike Cyterski, Data analysis, statistics**
- **Kate Sullivan, Hydrology, project lead**
- **Craig Barber, Fish effects**
- **Steve Kraemer, Groundwater**
- **Anne Neale, Megan Mehaffey, EnviroAtlas**
- **Lourdes Prieto, GIS, data acquisition**

Identifying the GKM Plume

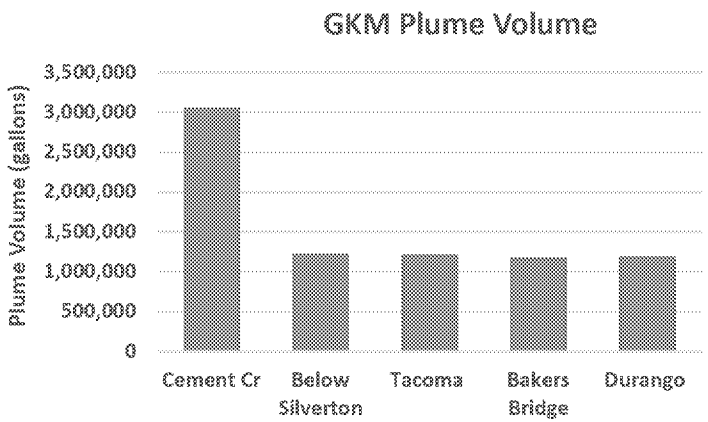
The Gold King Mine release traveled downstream from Cement Creek as a wave of water and a plume of metals

Wave was measured at USGS gages within first 100 km



Flow helpful in identifying plume from GKM to Durango

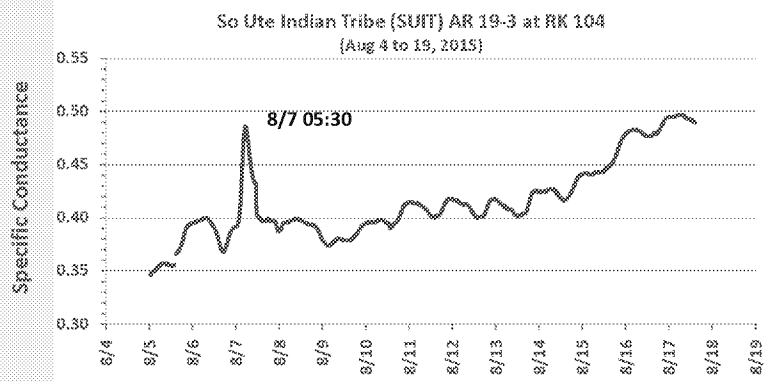
1.2 million gallons traveled as main body of plume (area under the plume peak minus baseflow)



For Cement Creek this volume represents the first 45 minutes of the release

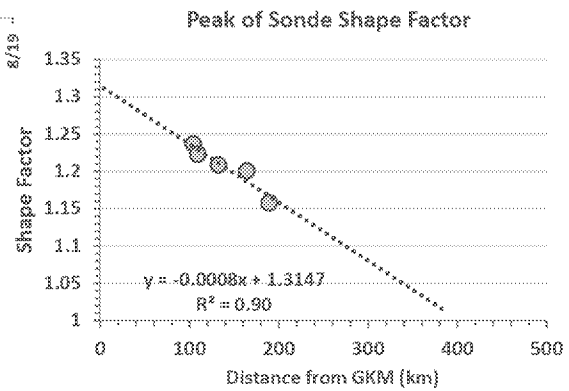
Identifying the GKM Plume

Sondes were helpful in identifying GKM plume in the Animas from Durango to Farmington

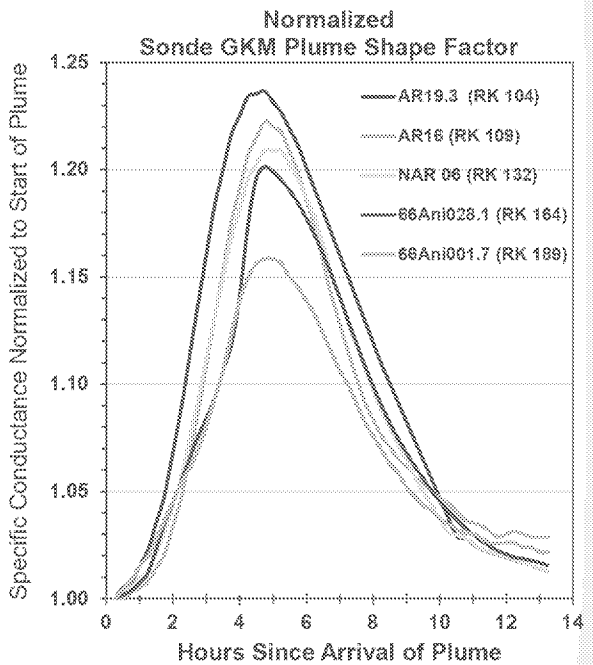


- **Bulk of plume concentration passed each location in 12 hours**
- **Plume maintained same "shape" as it travelled**
- **Relative peak declined (plume flattened)**

Shape factor suggests a sonde could not have detected the GKM plume by the time it reached Bluff Utah (RK 378)

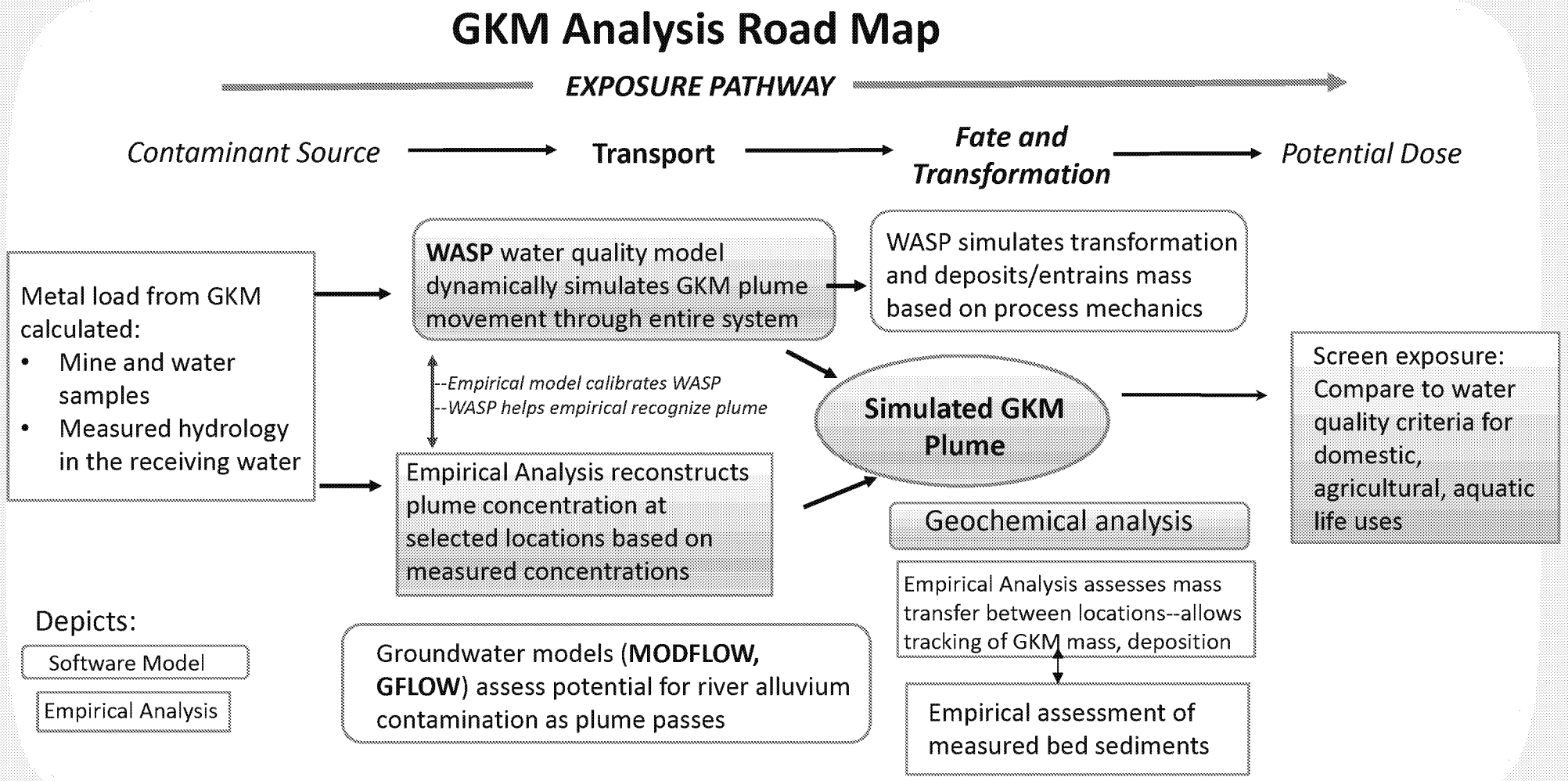


Computed as ratio of conductance at peak to conductance at start of rise

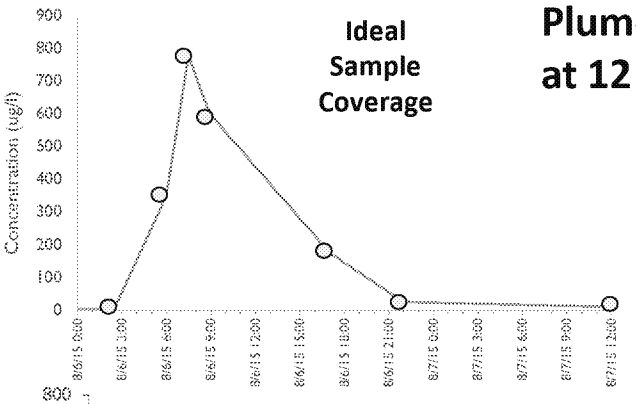


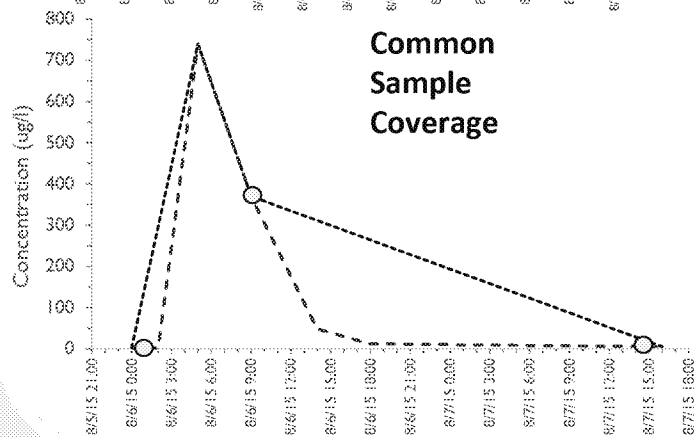
We refer to normalized constituent concentration through the duration of the plume as the "shape factor"

GKM Analysis Road Map



GKM Empirical Plume Modeling





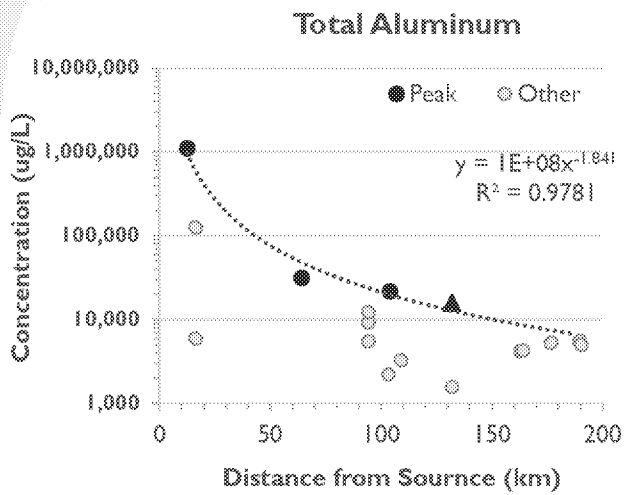
Plume concentration and mass empirically reconstructed from sample data at 12 sites (7 in Animas River and 5 in San Juan)

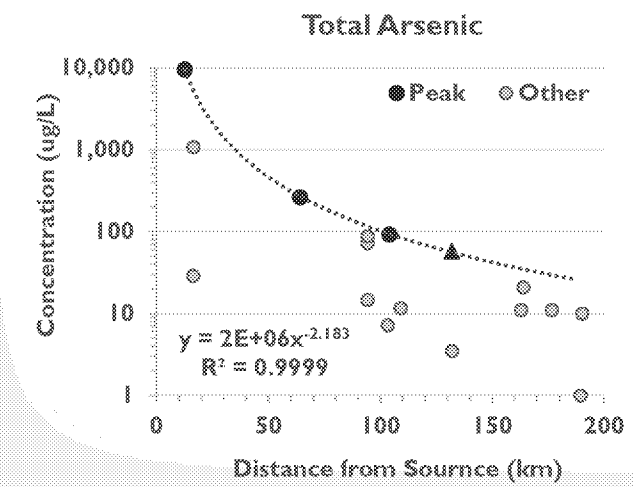
	Animas River	San Juan River
Samples During GKM Plume	~70	~72
Samples Very Near Peak	4 (Cement estimated, Bakers Bridge, SUIT sites AR 19.3 and NAR 06,	4 (NM 067SJ088.1, SJ4C and UDEP at 160 xing, UDEQ_SJ at Mex Hat

Combining all data: EPA Regions 6,8,9; N Mexico, Utah, Southern Ute Indian Tribe, Navajo Nation, U.S. Geological Survey

Most sites required us to establish peak concentrations to appropriately reconstruct the GKM plume

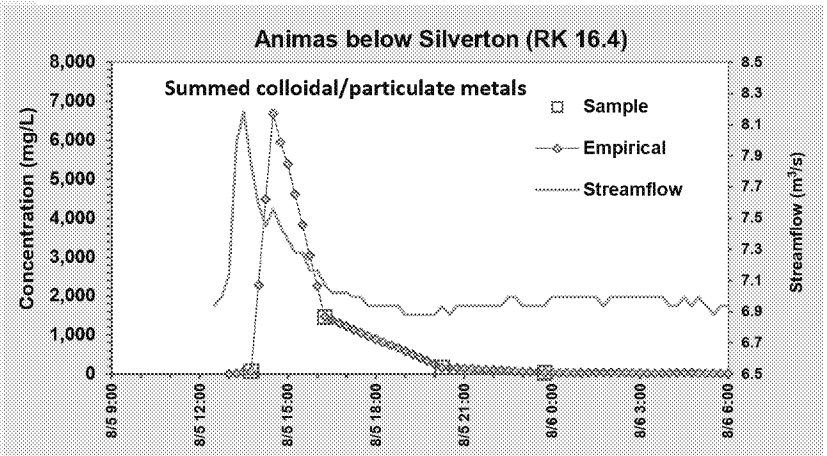
Empirical GKM Plume Construction Method



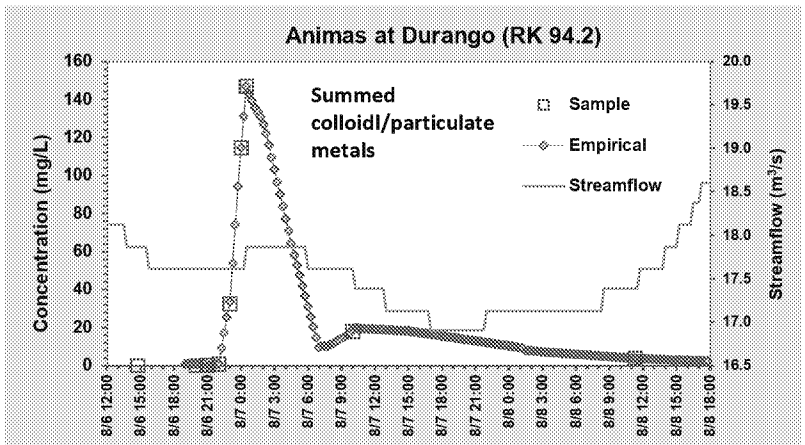


- **Determine plume shape from flow or sonde**
- **Animas River:**
  - **Peak concentration guided by most timely samples at each site and at watershed scale**
    - **4 sites measured very near peak used observed values**
    - **For others, peak of 8 key metals individually calculated with regressions (shown at left)**
    - **Metals Al, Ar, Cu, Mn, Fe, Pb, Ni, Zn show strong trend like those shown**
    - **Actual regressions used the natural log of concentrations (R^2 of each > 0.98)**
  - **Interpolate concentrations between observed and estimated values**
- **San Juan River:**
  - **No comparable relationships for estimating peak**
  - **Interpolate between observed values only**

Examples of Empirical Reconstruction of GKM Plume
Summed Colloidal/Particulate Metals associated with Plume



Background metals removed in this illustration

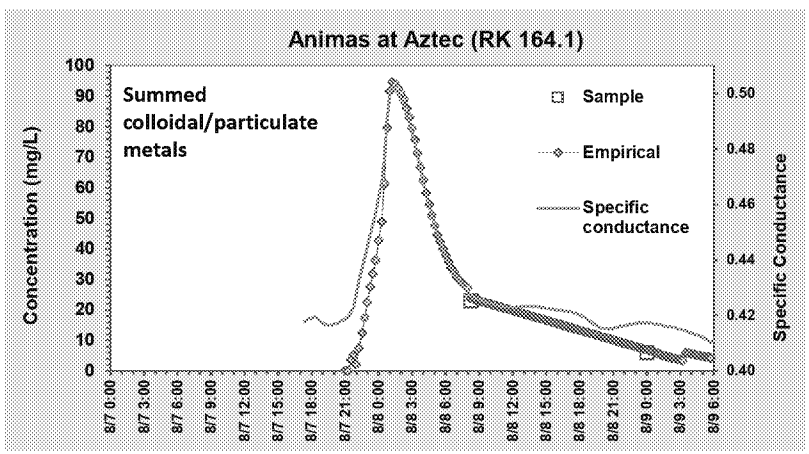


--Metals concentrations estimated every 15 minutes

--Concentrations multiplied by flow volume every 15 minutes from USGS gage data to compute mass

--Mass summed for plume period to determine GKM metals delivery

- Observed data anchors all calculations
- Errors possible with every choice
- Errors don't tend to propagate to next site



Gold King Mine WASP Model

The WASP Modeling Framework was used to develop

- The "Gold King Mine WASP Model" ("WASP Model")

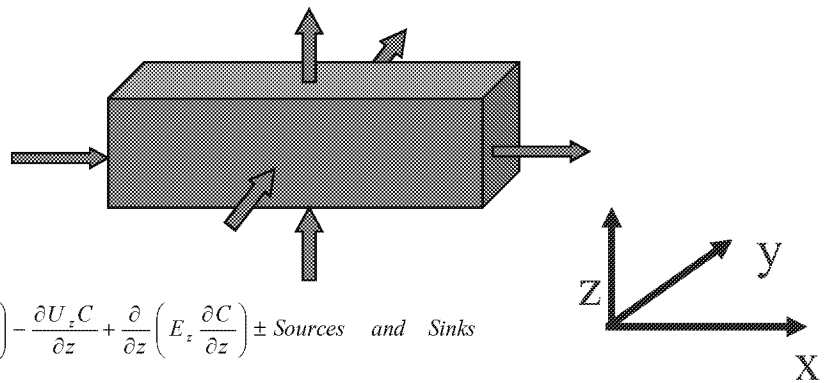
This was designed to investigate

- Movement and timing of the plume release
  - Time for the plume to reach a location
  - Duration of the plume at a location

- Concentrations in surface waters and sediments
  - Total Particulate Metals
  - Total and Dissolved Arsenic, Copper, Lead, and Zinc

WASP Modeling Framework

Control Volume



$$\frac{\partial C}{\partial t} = -\frac{\partial U_x C}{\partial x} + \frac{\partial}{\partial x}\left(E_x \frac{\partial C}{\partial x}\right) - \frac{\partial U_y C}{\partial y} + \frac{\partial}{\partial y}\left(E_y \frac{\partial C}{\partial y}\right) - \frac{\partial U_z C}{\partial z} + \frac{\partial}{\partial z}\left(E_z \frac{\partial C}{\partial z}\right) \pm Sources \quad and \quad Sinks$$

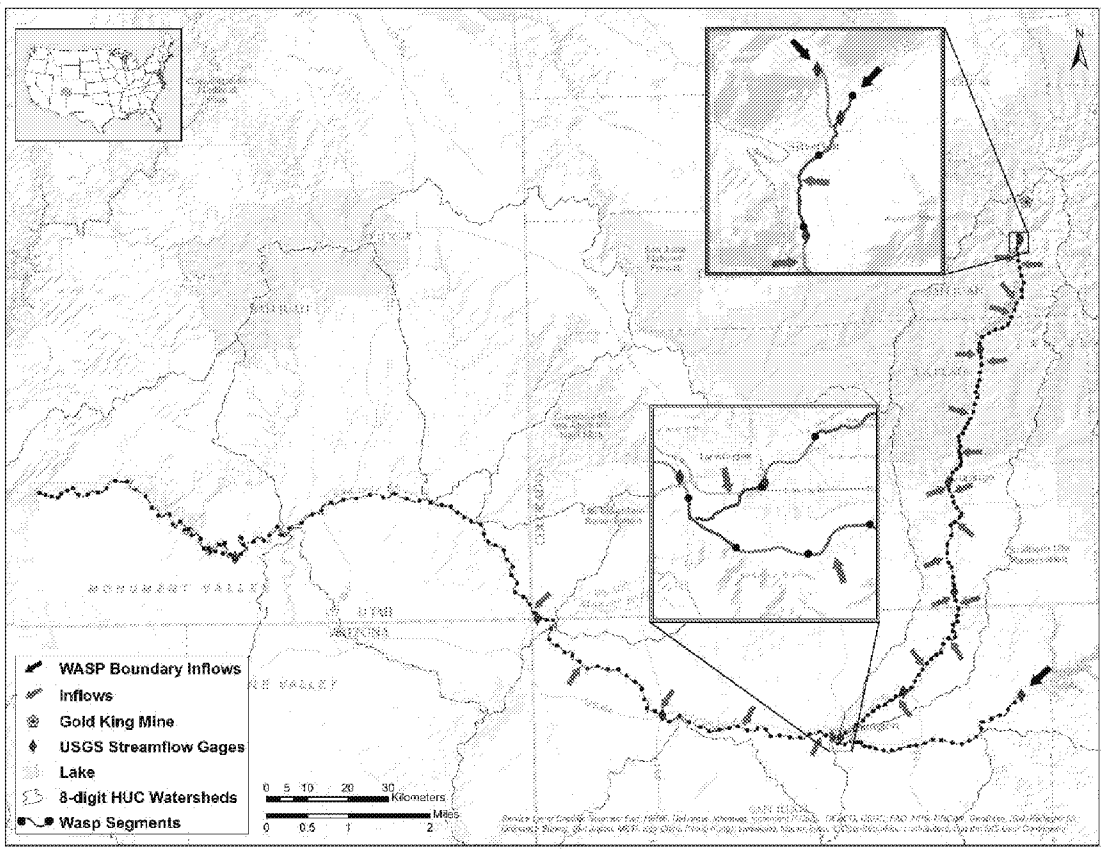
- Dynamic differential mechanistic mass balance
- Simulates concentrations in surface water and sediments
- Spatially and temporally explicit
- Range of Water Quality Problems
- Separation of Processes
  - Transport (Advection, Dispersion, Settling, Resuspension)
  - Kinetics (Sorption)
- Simple hydrodynamic modeling approaches for water routing

Model Parameterization: Segments

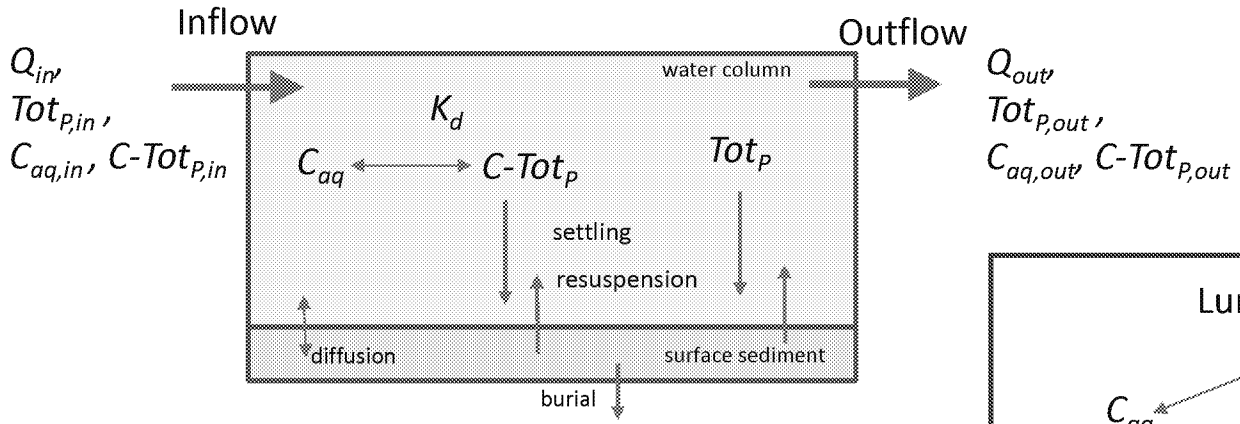
- BASINS used to download shapefiles for the Animas and San Juan Rivers
- NHDPlus dataset to delineate model domain
- WASPBuilder tool to construct WASP segmentation
- Stream network edited to include/remove segments until boundaries were continuous, non-branching/non-braiding
- Segments were divided into lengths with approximately equal travel time, defined using length and slope.
- Total of 458 WASP segments
  - 229 surface water and 229 sediment layer segments
- Average length: 2447 m
- Minimum length: 922 m
- Maximum length: 4655 m

Model Domain and Set Up

- **Three upstream boundaries**
  - Cement Creek
    - upstream confluence w Animas
    - downstream of Gold King Mine
  - Animas River
    - upstream of Cement Creek
  - San Juan River
    - upstream of Animas
- **USGS gage flow**
  - Flows divided along stream to match gages



Gold King Mine WASP Model: Conceptual Model



Q: flow into and out of each segment (m^3/s)

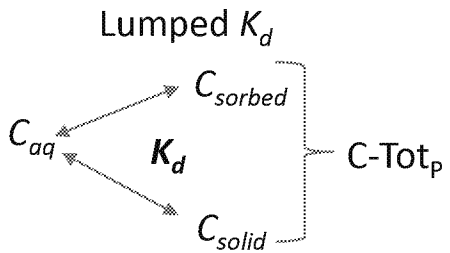
Tot_P: Sum total of all particulate metals in the system (mg/L)

C_{aq}: Filtered individual metal concentration (mg/L)

$C\text{-}Tot_P$: Particulate metal (mg/L)

$C_T = C_{aq} + C\text{-}Tot_P$: Unfiltered individual metal concentration (mg/L)

K_d= coefficient for partitioning metal between dissolved and total fraction

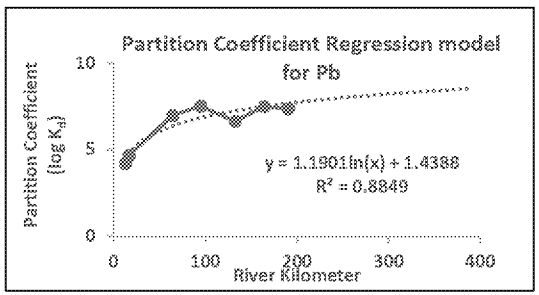


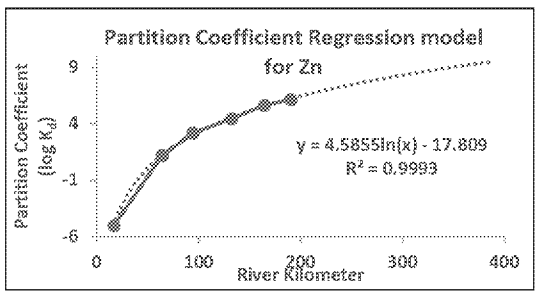
We use K_d as a lump parameter. A dissolved metal can sorb onto particulates or it can mineralize and precipitate out of solution. We lack sufficient geochemistry data to discern between these two, so we use a lumped parameter term, K_d, developed using empirical data.

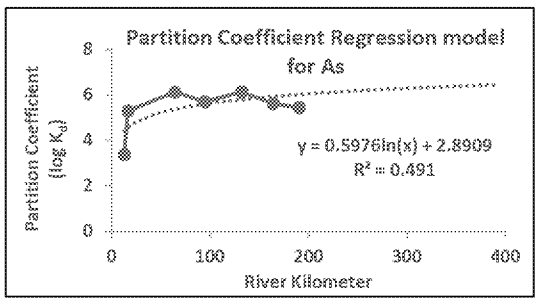
Parameterizing WASP: K_d

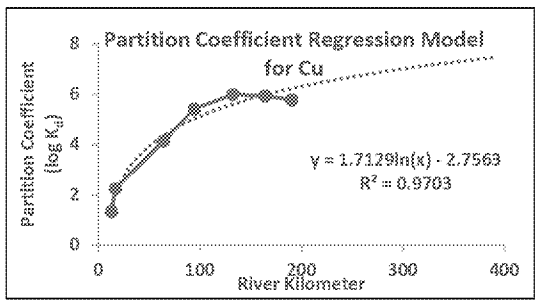
River Km	Total Particulate (mg/l)	Total (mg/l)				Dissolved (mg/l)			
		As	Cu	Pb	Zn	As	Cu	Pb	Zn
12.5	39,108.4	29.052	129.551	631.870	155.320	0.301	70.916	1.029	157.118
16.4	7,193.9	5.400	24.100	128.000	34.200	0.004	10.716	0.385	30.552
64	818.6	0.554	2.352	12.012	3.906	0.001	0.189	0.002	1.700
94.2	269.0	0.149	0.672	4.454	1.666	0.001	0.010	0.001	0.187
132	103.9	0.058	0.232	1.410	0.535	0.000	0.002	0.003	0.011
164.1	42.6	0.017	0.074	0.345	0.270	0.001	0.002	0.000	0.004
190.2	39.7	0.015	0.065	0.300	0.240	0.001	0.003	0.000	0.005

Supported by modeling of dissolved metal concentrations invoking electrostatic and chemical equilibrium with suspended colloidal $Fe(OH)_3$ where observed dissolved values are used to solve for sorption site density







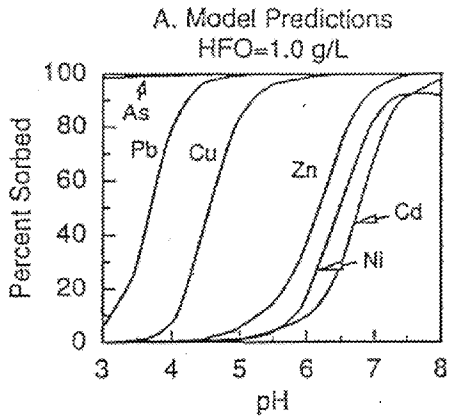


K_d was calculated using empirically-estimated peak concentration data.

A regression was used to develop a relationship for K_d versus distance.

The value for K_d at 200 km was used for the length of the San Juan River

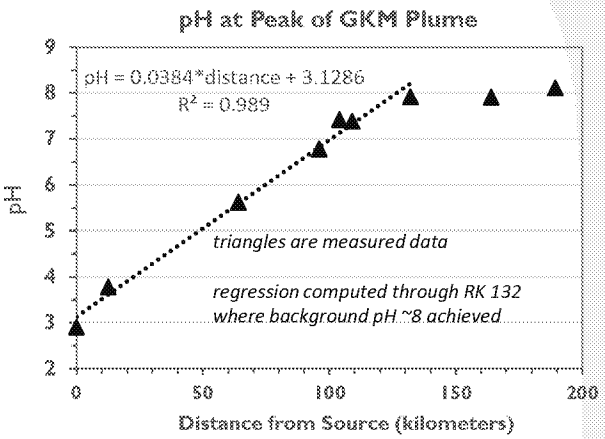
Transition of Metals from Dissolved to Solid Phase



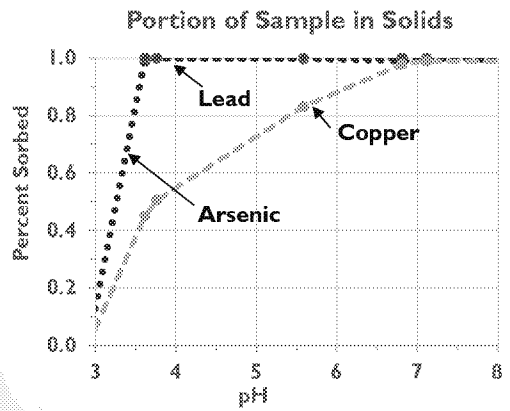
Individual metal ions sorb to solids in specific pH ranges

Graph of "sorption edge" at left shows range of pH for 6 metals of interest (e.g. Smith 1995, graphic from Church et al. 1997)

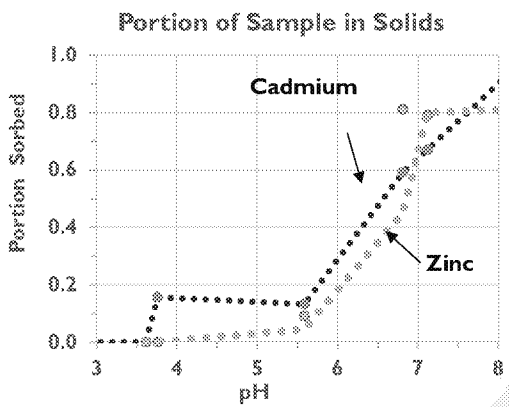
Animas River samples can be translated from distance to pH with this relationship to mimic the sorption curve



Sorption of metals to solid forms in the Animas River followed the pattern of pH increase



- **Metals that sorb at low pH existed in dissolved form only in Cement Cr and in Silverton area where pH < 4**
- **Dissolved copper persisted to Durango where pH reached 7**
- **Metals that sorb at higher pH traveled farther downriver in dissolved form into lower Animas**

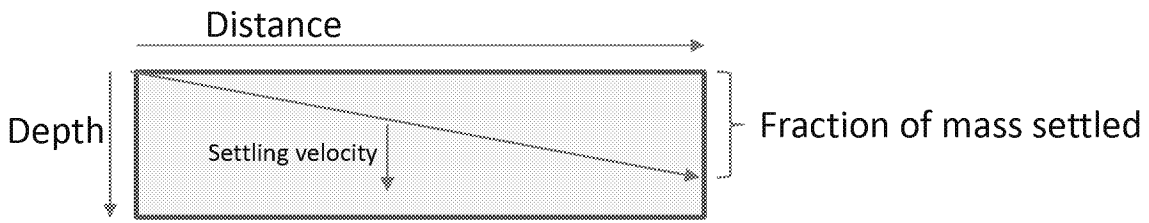


Parameterizing WASP: Settling Velocity

River Km	Total Mass (kg)	Avg Depth (m)	Time to travel (s)	Fraction Mass settled	Stream Velocity (m/s)	Settling Velocity (m/d)	Associated Particle Size, diameter (mm)
12.5	489,636	1.7	4,251	0.246	0.92	8.4	0.010
16.4	369,131	2.0	68,058	0.173	0.70	0.4	0.002
64.0	305,100	1.8	37,102	0.690	0.81	2.9	0.006
94.2	94,546	1.7	46,312	0.161	0.82	0.5	0.003
132.0	79,364	1.9	37,805	0.379	0.85	1.7	0.005
164.1	49,268	2.7	30,269	0.100	0.86	0.8	0.003

Silt-sized particles

Empirically-estimated total mass at different locations used to estimate settling velocity



$$Time\ of\ Travel = \frac{Distance}{Stream\ Velocity}$$

$$Settling\ Velocity = Fraction\ Mass\ Settled * \frac{Average\ Depth}{Travel\ Time}$$

WASP Parameterization

Parameter		Source
Stream Description	Segment Length, Width, Depth, Volume, Slope	BASINS, NHDPlus
Hydraulic Geometry	Velocity and Depth Exponent	USGS Gage Cross-section, Regression
Bottom Roughness	Manning's Roughness	Calibrated
Stream Flow		USGS Gages
GKM Release Load		Estimated from Empirical Data
Settling Velocity		Estimated from Empirical Data
Partition Coefficients		Estimated from Empirical Data

Synergy of Modeling Approaches

Both models begin at concentrations estimated for Cement Creek at peak

Estimated Concentration Cement Creek 12:45 Aug 5, 2015

Analyte	Fraction, mg/L Dissolved	Colloidal/ Particulate	Total
Aluminum	619	2,717	3,336
Antimony	0.02	1.12	1.13
Arsenic	0.30	28.75	29.05
Barium	0.07	34.28	34.35
Beryllium	0.23	0.25	0.48
Cadmium	0.67	0.00	0.58
Calcium	2,438	-836	1,603
Chromium	0.01	2.49	2.49
Cobalt	1.26	0.09	1.36
Copper	70.92	58.63	129.55
Iron	268	34,785	35,053
Lead	1.03	630.84	631.87
Magnesium	196.9	787.9	984.9
Manganese	205.91	69.43	275.34
Mercury	0.00	0.07	0.07
Molybdenum	0.02	7.07	7.10
Nickel	0.55	0.43	0.97
Potassium	40.62	707.74	748.36
Selenium	0.03	0.85	0.88
Silver	0.02	3.90	3.92
Sodium	17.99	64.61	82.60
Thallium	0.02	0.42	0.44
Vanadium	0.06	19.25	19.31
Zinc	157.12	0.00	155.32
Sum (All)	4,019	39,084	43,101
Major Cations (Ca,K, Mg, Na)	2,694	725	3,418
Total Metals (w/o major cations)	1,325	38,360	39,683

Empirical Model

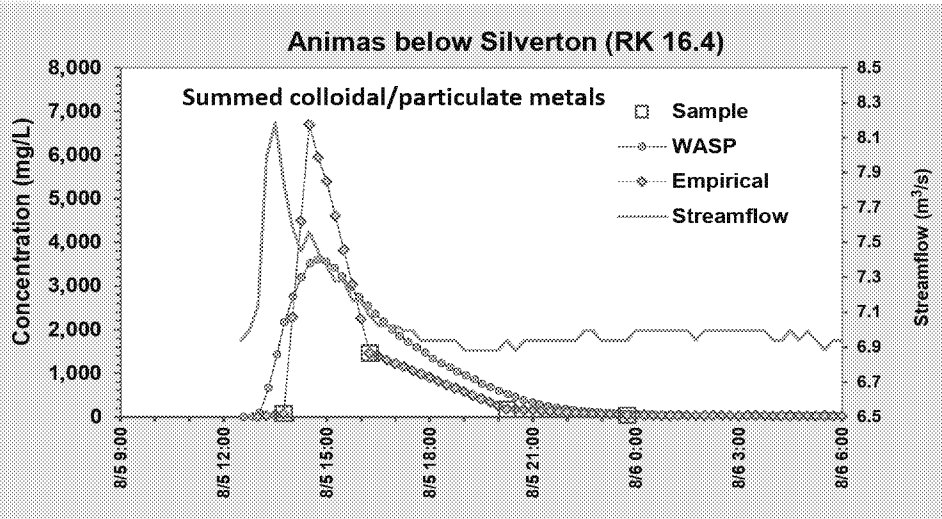
- Reconstructs plume at 12 locations based on observed data
- Locations selected based on nearby USGS gages and availability of sampling data, often multiple agencies
- Identifies plume based on flow, sondes, or with assistance of WASP
- Computes concentrations for dissolved and colloidal/particulate solids from field sampled data as plume passes the site
- Computes mass of dissolved and colloidal particulate solids as plume passes the site
- Partitions between dissolved and colloidal based on sample data

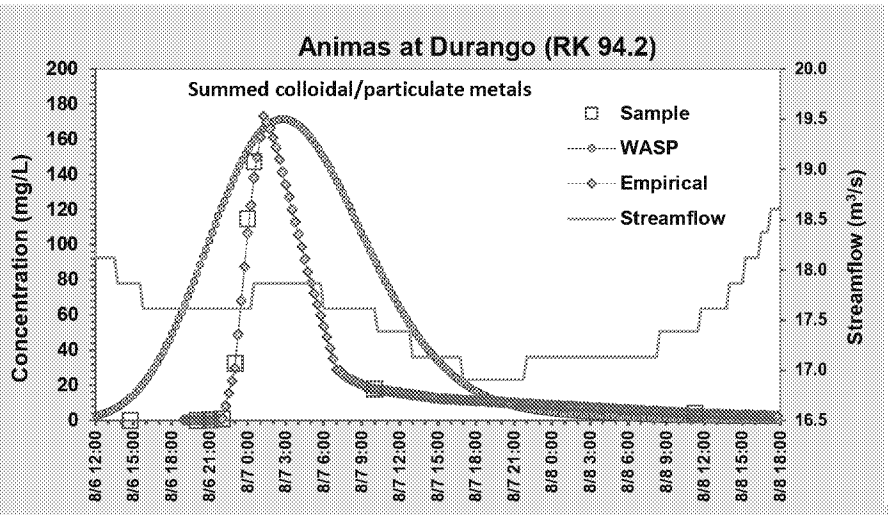
WASP WQ Model

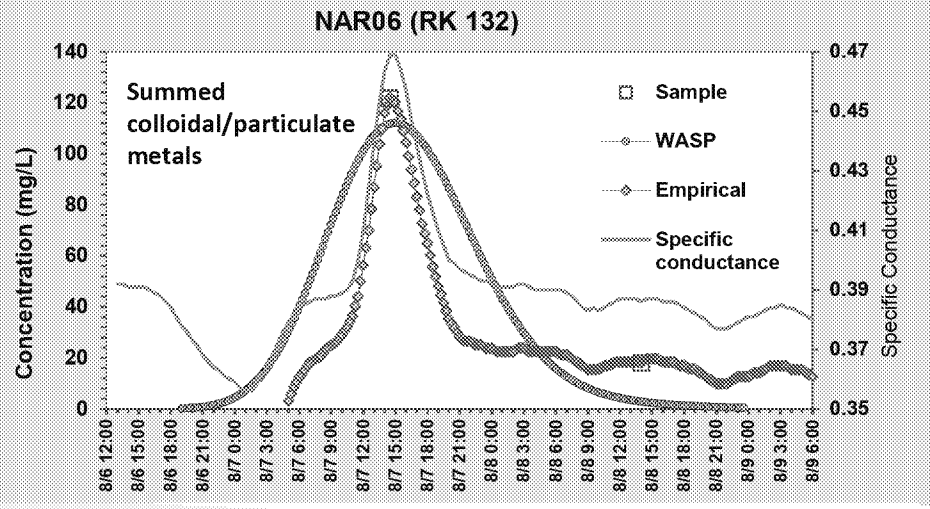
- Water quality modelling software dynamically transports pollutants downstream from source
- River segments ~ 2 km in length
- Moves water from segment to segment adding water at joining streams
- Suspends and deposits particles during transit according to velocities relative to particle size
- Particle settling parameterized using metal mass developed empirically from observed data
- Empirically partitions metals from dissolved to colloidal/particulate solids calibrated to sample data

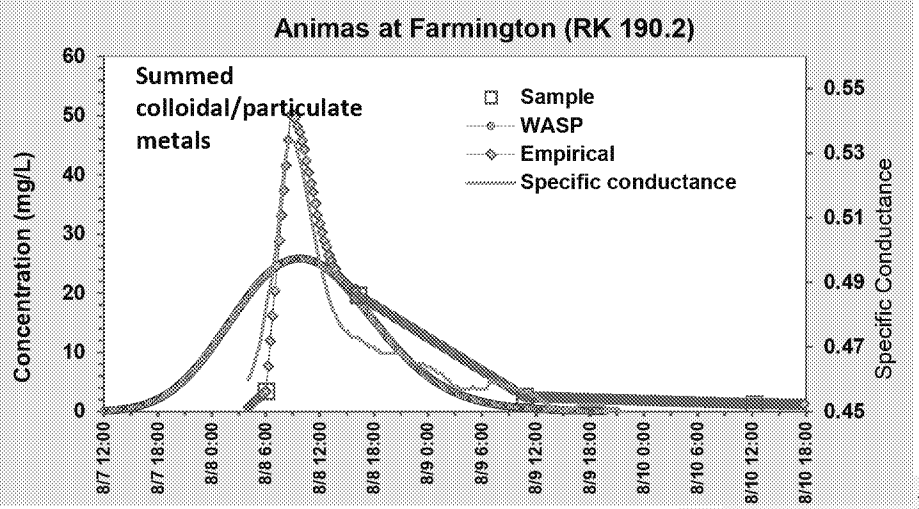
The two approaches support one another but do not necessarily produce the same results.

Comparison of GKM Plumes modeled with Empirical and WASP models

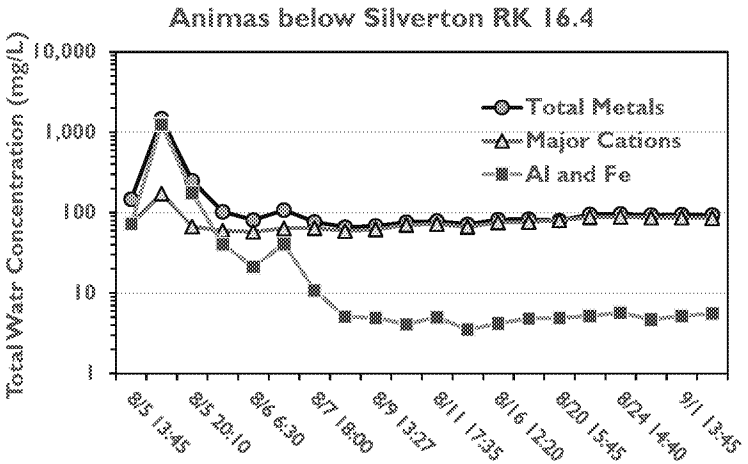


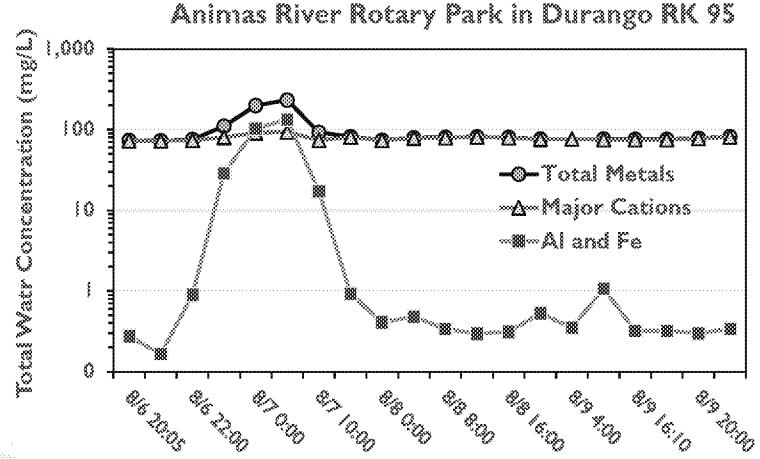


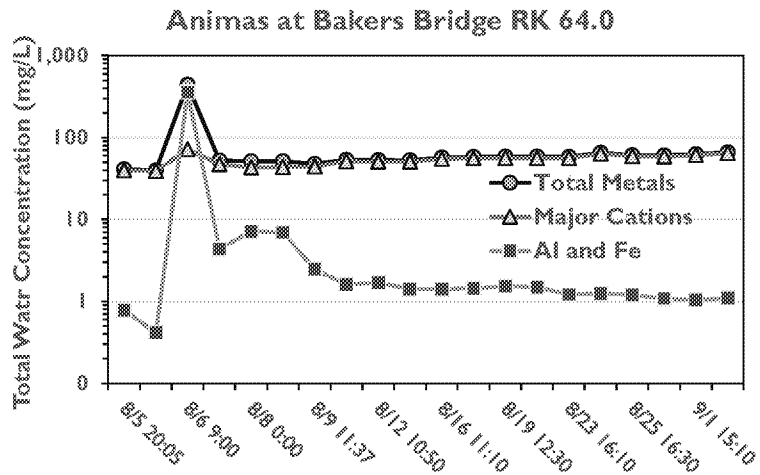




Sample Data At Locations Followed Plume Pattern and Generally Returned to Near Pre-event Concentrations Quickly





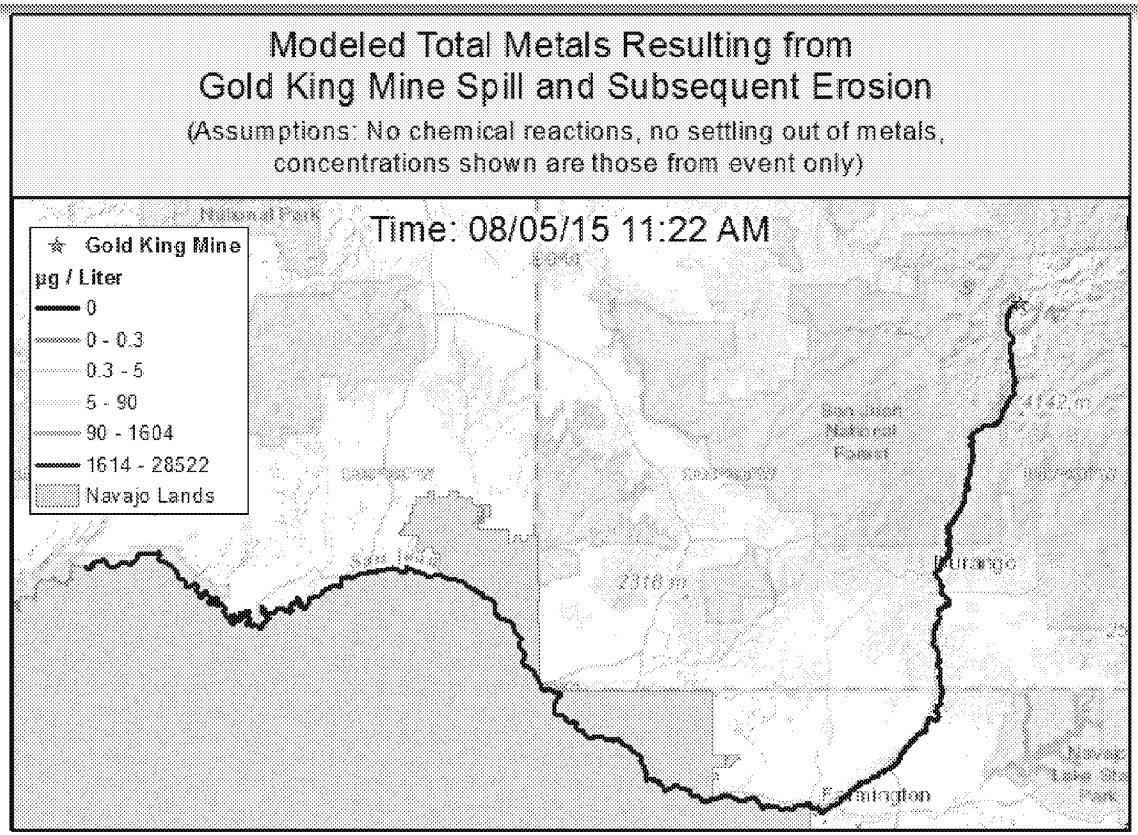


- Shown are 3 sites with best sampling during plume event in upper Animas
- Concentrations returned towards pre-event levels soon after the plume passed
- Water quality during the post event period will be explored in detail in Session 3

Animation of GKM plume

Concentrations of total summed metals estimated by WASP as plume traveled 600km from source through Animas and San Juan Rivers

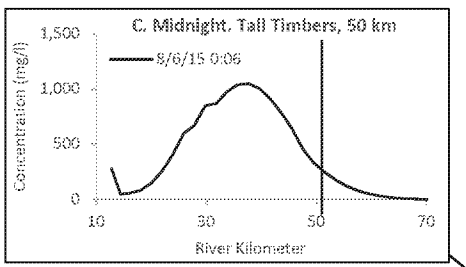
Animation produced using EnviroAtlas web-based tool



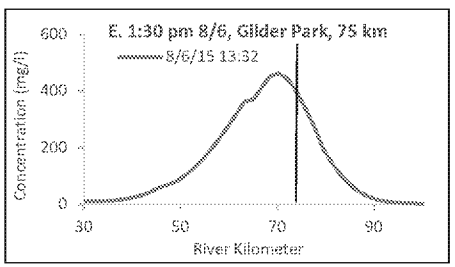
WASP estimated location of GKM plume compared to real-time observations reported in the Denver Post as the event occurred

The line on each graph shows the location and time of the observation relative to the full location of the plume at that time

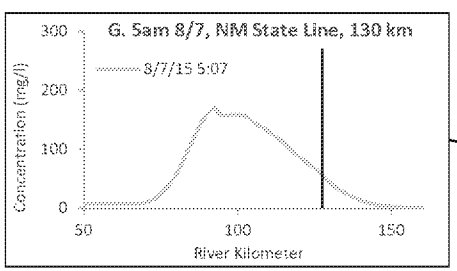
Tall Timbers Resort

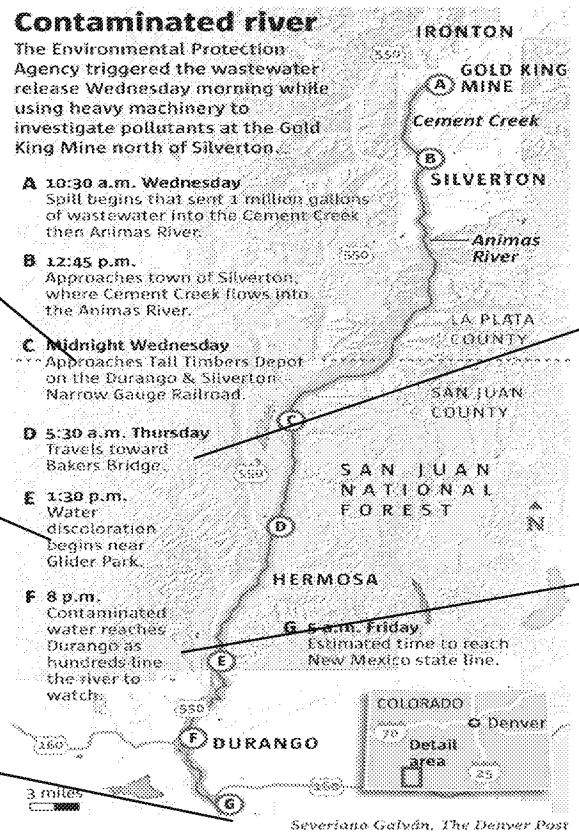


Gilder Park

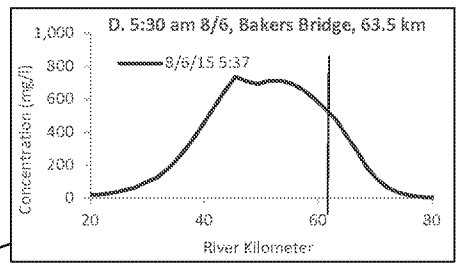


Colorado / New Mexico state line

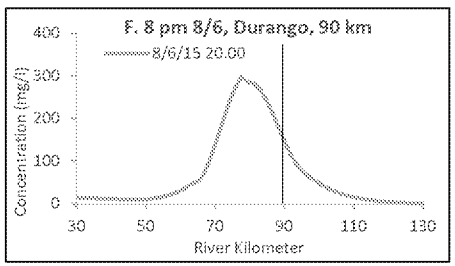




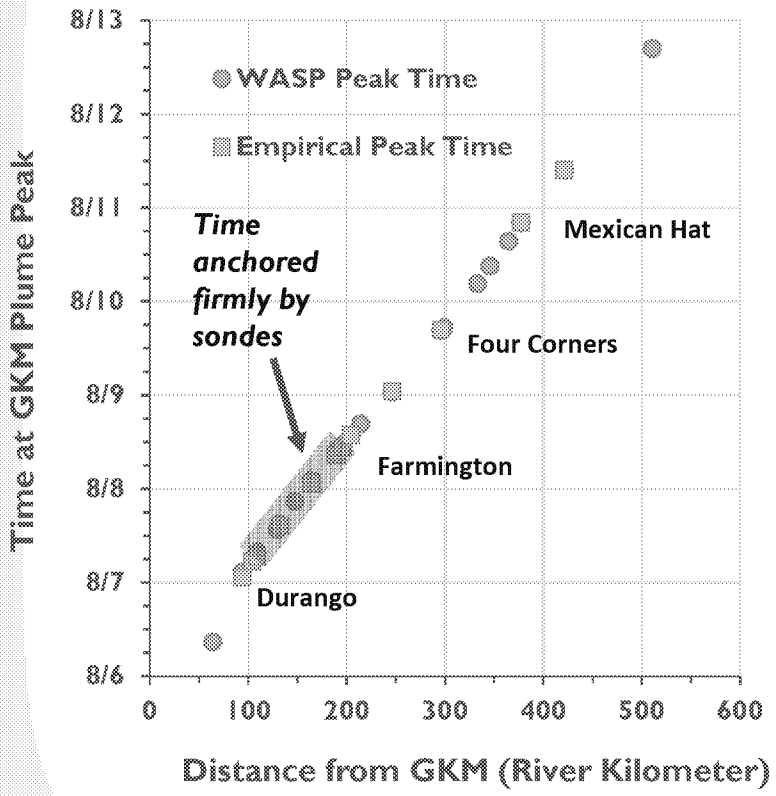
Baker's Bridge

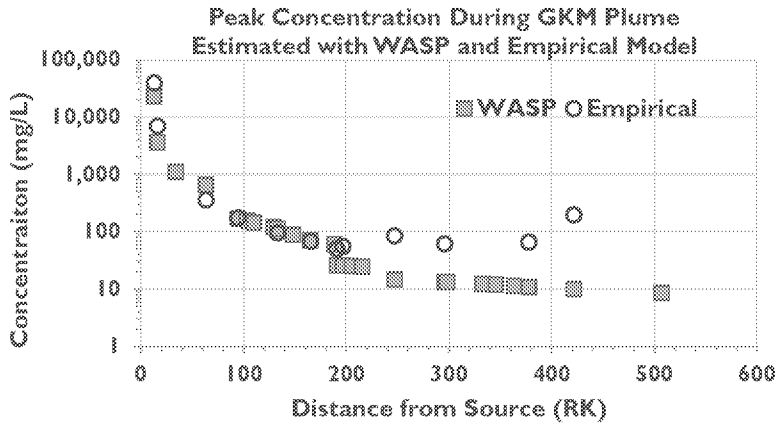


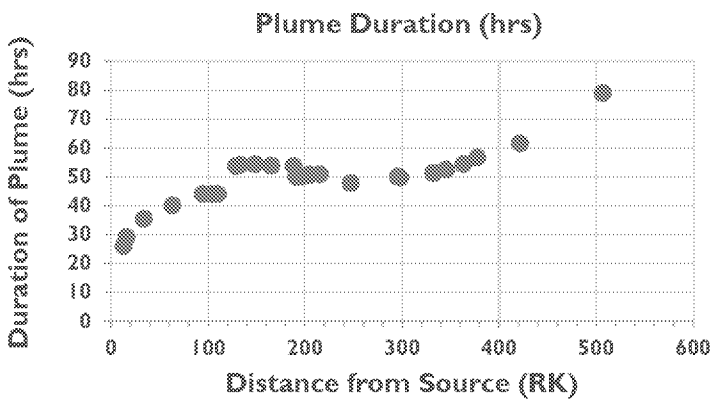
Durango



Modeled Plume Characteristics







- Plume timing firmly established by sondes from 100 to 200 km
- WASP guides travel time through the San Juan River
- Peak metal concentrations decline as plume travels
- Duration of the plume increases as it travels

Ave. Velocity:
0.9 m/s
3.1 km/hr or 1.3 miles/hr

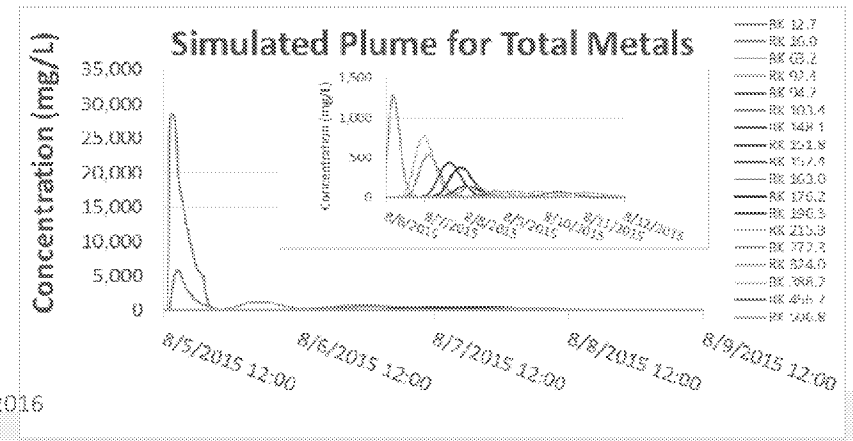
WASP Simulations: Plume Travel Time

River Distance (km)	Site	Plume Duration (Days)	Time to Peak Concentration (hrs)
12.54	Cement Creek	1.0	0.7
16.4	Animas at Silverton	1.0	2.2
33.8	USGS gage at Tacoma	1.2	9.8
63.8	Animas at Baker's Bridge	1.3	20.2
94.2	Animas at Durango	1.6	38.1
104.0	So Utes AR19.3	1.6	41.3
109.0	So Utes AR16	1.6	43.2
129.6	USGS at Cedar Hill 9363500	1.7	48.9
132	SoUtes NAR06	1.7	50.4
147.5	ADW 022	1.7	56.1
164.1	At Aztec ADW 010, NM66Animas028.1	1.8	61.6
189.4	NMED 66Animas001.7, FW 040	1.8	68.4
190.2	Animas at Farmington (FW040)	1.8	69.3
196.1	San Juan at Farmington (FW020)	1.8	70.7
196.9	San Juan at LP	1.8	70.7
204.4	NM 67SanJua088.1	1.9	73.1
204.5	LVW-030	1.9	73.1
214.4	SJFP	1.9	76.0
246.3	SJSR	1.9	84.2
295.8	SJ4C	2.1	100.0
298.7	Utah 160 Xing	2.1	100.7
333.2	SJME	2.2	112.0
345.7	Utah nr Montezuma	2.3	116.6
345.8	SJMC	2.3	116.6
364.8	Utah Swinging Footbridge	2.4	122.8
377.1	Utah Sand Island	2.5	127.6
377.6	SJBB	2.5	127.6
421.3	SJMH	2.7	141.1
421.5	Utah Mexican Hat	2.7	141.1
510.7	Utah Clays Hill Ramp	3.3	172.2

For each river location identified by a sampling site:

- **plume duration defined as the time for 99% of the plume to pass**
- **time since the initial release at GKM for the plume peak concentration to reach that location**
- **EPA, New Mexico, Utah, Southern Ute Indian Tribes included in table.**

Duration ranged from 1 to 3.3 days. Increasing in duration as plume traveled downstream.

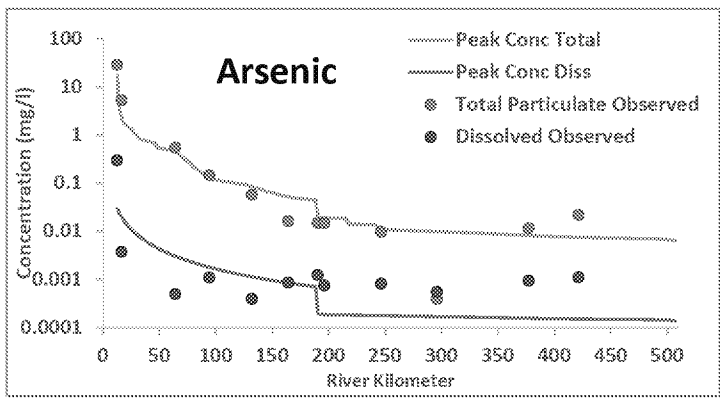


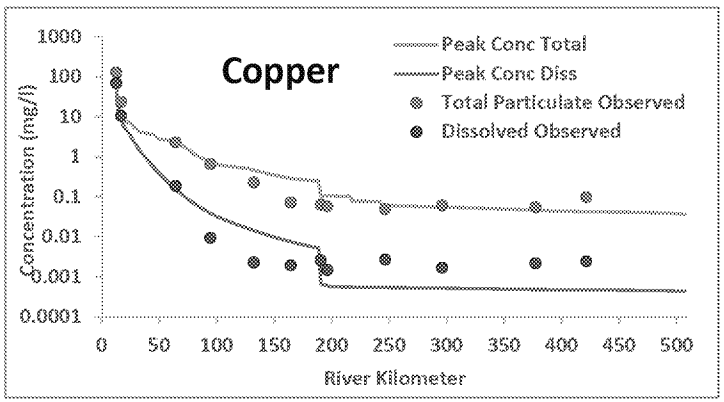
Longitudinal Patterns in Water Quality

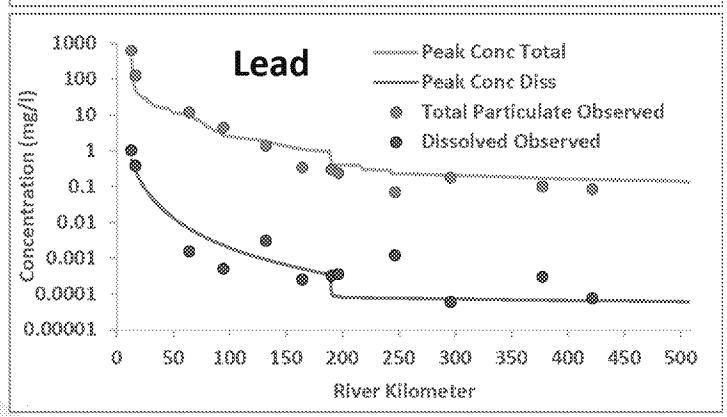
Analysis Focus	Informs	Approach	
Longitudinal and temporal patterns of metal concentrations mg/l	Exposure potential for various uses of water (drinking, irrigation, recreation)	• Straightforward graphing of concentrations • WASP modeling • Animated visualization	**Session 2**
Metals Mass (kg) (concentration x flow)	Enables tracking fate of Gold King Mine metals	Reconstruct GKM plume loads at individual sites as plume passed	**Session 3**

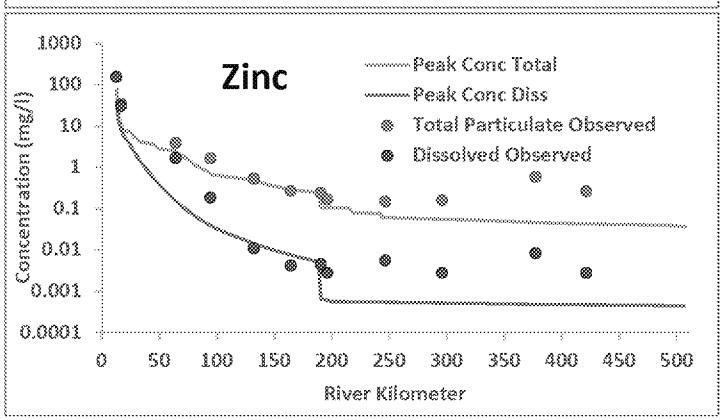
WASP modeling of individual metals

Peak simulated total and dissolved concentrations and empirically-estimated peaks









Highlights

- **Orders of magnitude differences along the rivers**
- **Animas has strong decline in downstream direction**
- **And between total and dissolved**
- **Zinc remained dissolved longer than other metals (consistent with pH)**

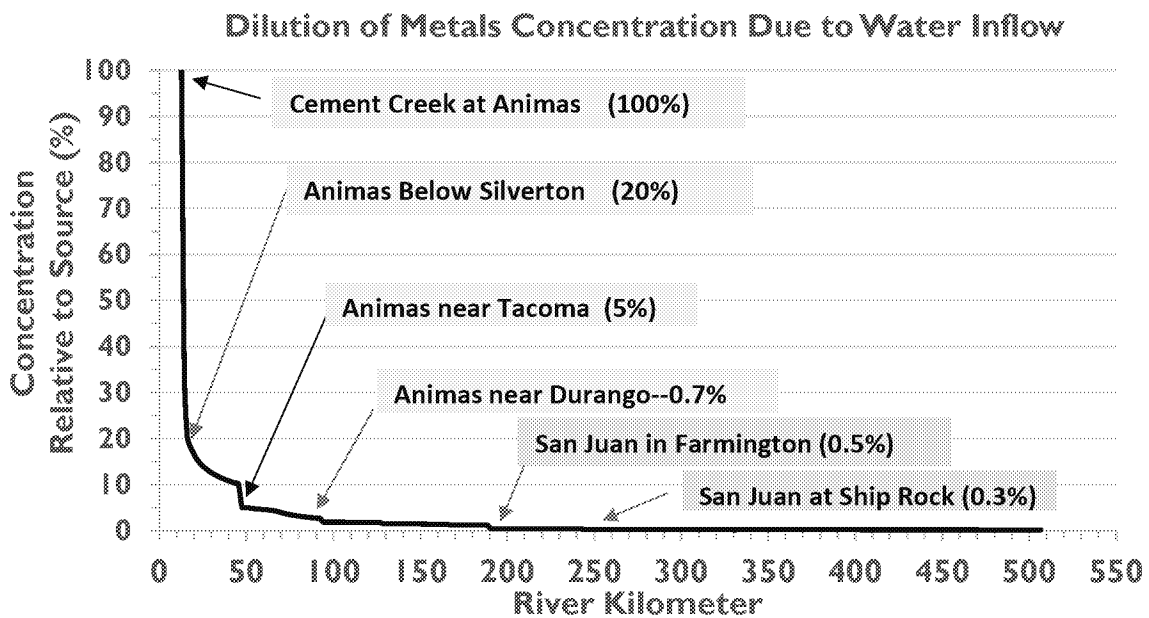
Longitudinal Trends in Water Quality

- Metal concentrations declined by 4 to 5 orders of magnitude from those estimated in Cement Creek at the peak of the GKM plume
- Almost all of this decrease occurred in the Animas River
- What contributed to this decline?

Likely affect of various factors on metals concentrations as GKM plume migrated downstream through the Animas River

FACTOR	DISSOLVED	COLLOIDAL /PARTICULATE
Dilution	Decrease	Decrease
Acid neutralization drives transformations	Decrease	Increase
Deposition	-	Decrease

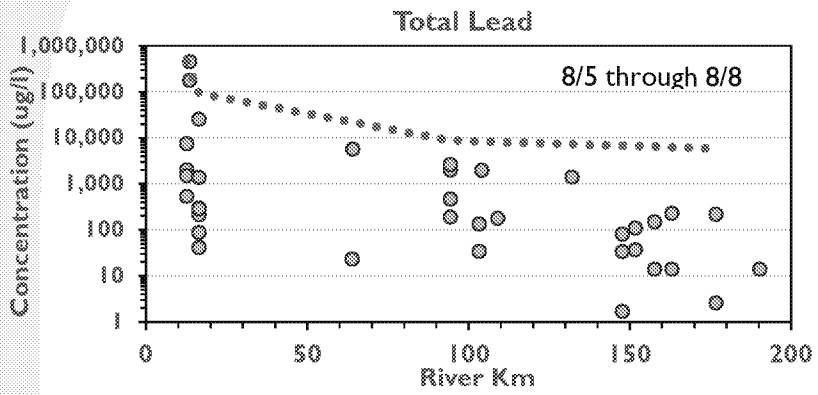
Dilution

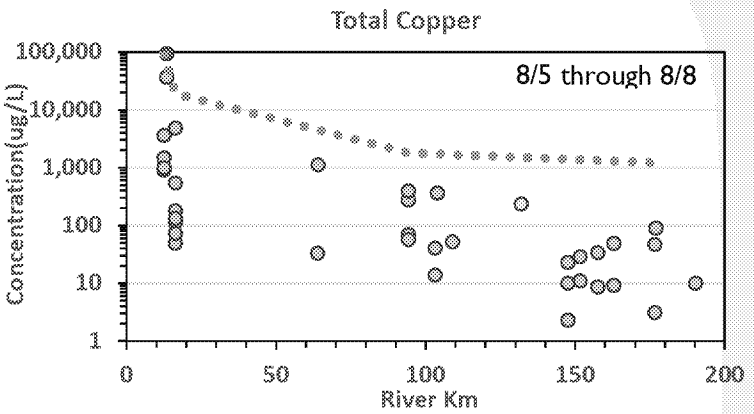


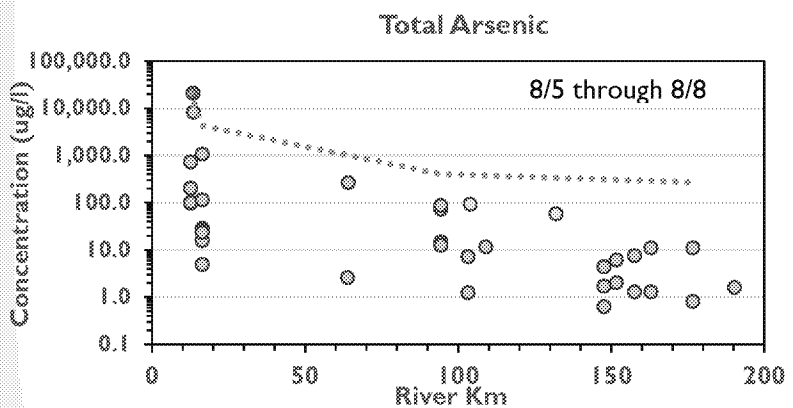
WASP modeling was effective in quantifying dilution because it tracks hydrologic change along the river

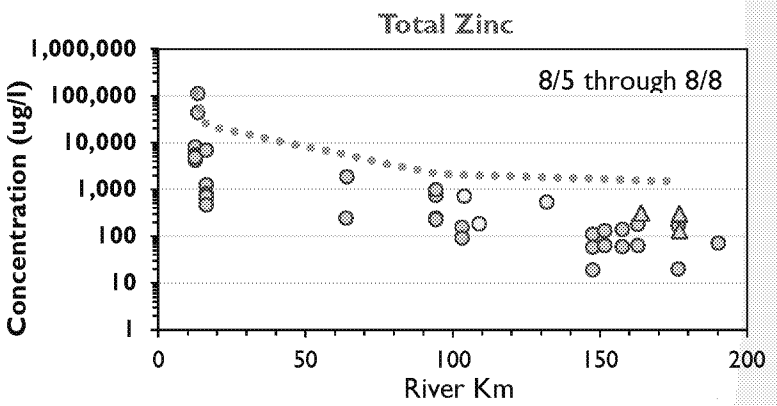
- **Metals concentrations in the GKM plume were strongly diluted with incoming flow to the Animas River as the plume flowed south**
- **Metals concentrations were diluted to 20% below Silverton after 4 kilometers of travel as Upper Animas, Mineral Creek and Cement Creek join in this area**
- **San Juan at Farmington concentrations could not have been more than 0.5% of what was observed in Cement Creek**

Longitudinal Trends in Observed Total Water Concentrations in the Animas









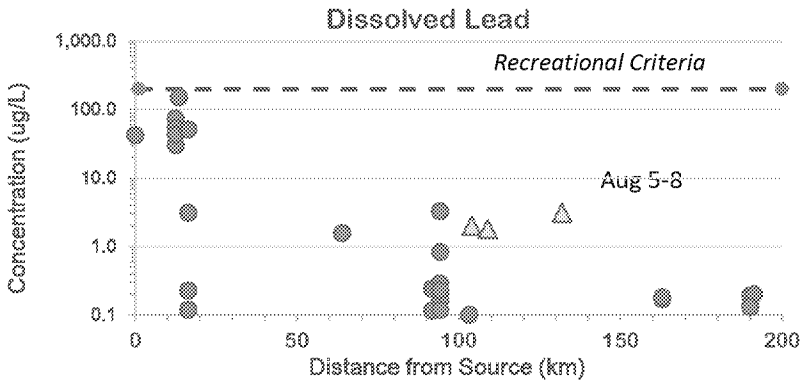
- **Metals concentrations generally followed the dilution pattern computed by WASP (shown as dotted orange line)**
- **Several orders of magnitude decline as plume traveled from source**
- **Most observed data lower than predicted by dilution alone indicating losses from deposition**
- **All metals behaved as shown for these 4**

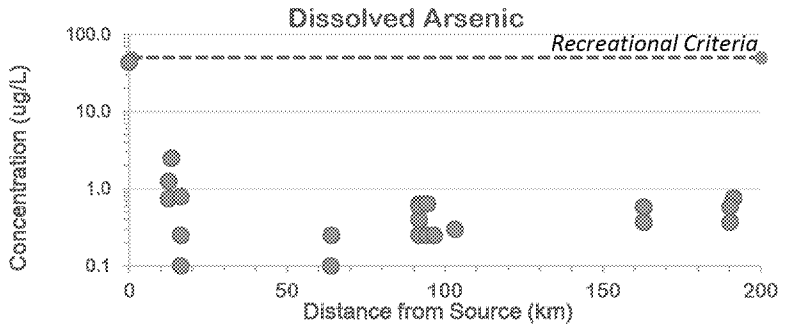
Grey circles: EPA
Yellow circles: So. Ute Indian Tribe

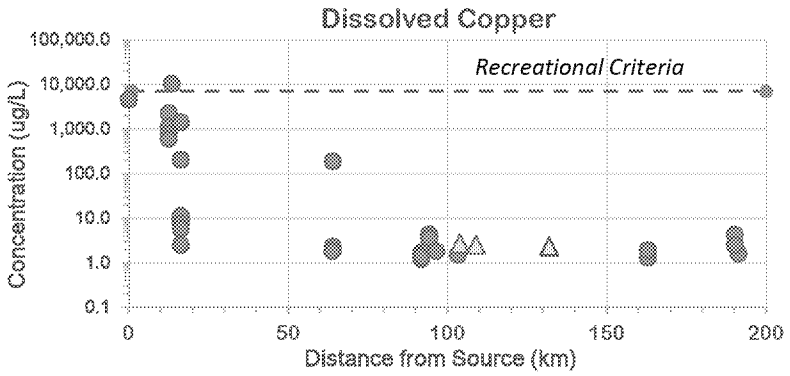
Green triangles:
New Mexico Environment Department

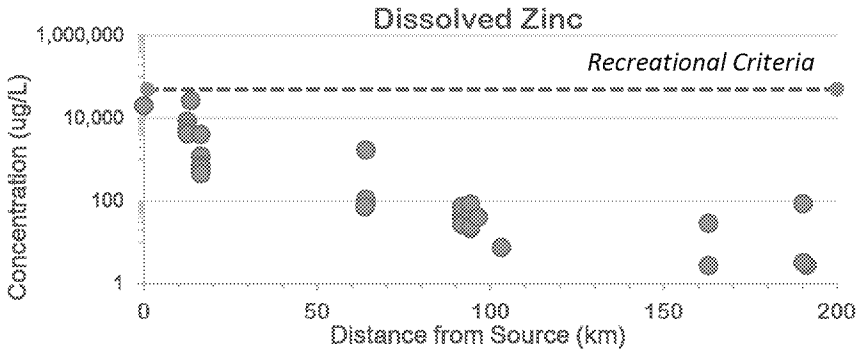
Longitudinal Trends in Observed Dissolved Metal Concentrations in the Animas

- **Dissolved concentrations of metals were much lower than total of metals but were high in headwaters near the GKM release**
- **Followed dilution pattern with orders of magnitude decrease in the Animas**
- **Dissolved metals declined to background by the time the plume reached the lower Anima**

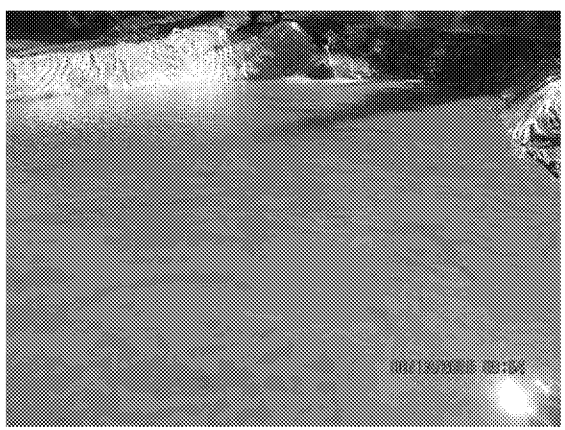








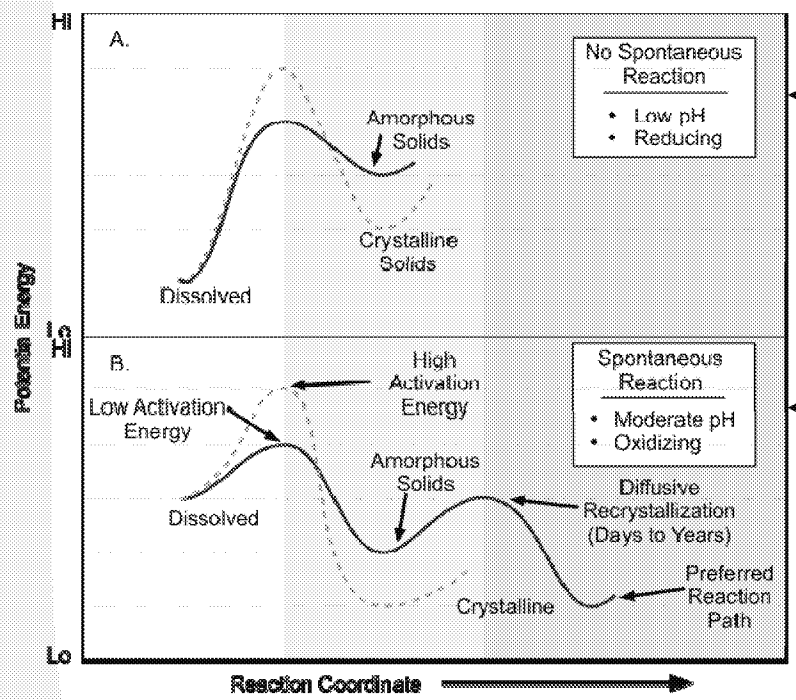
Geochemical Transformations During GKM Plume Movement



Yellow boy formation with acid neutralization in a treatment pond

- **Two major concerns with acid mine drainage**
  - **Low pH**
  - **High concentrations of dissolved metal ions**
- **The toxicity associated with dissolved metals of the GKM release (pH~2.9) was naturally mitigated once the AMD entered the Animas River system (pH 6-8)**

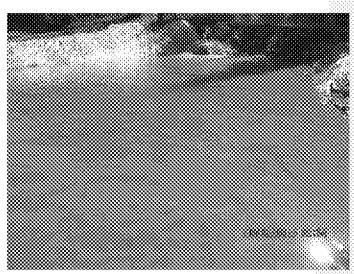
AMD Neutralization



- **Under conditions expected in a deep subsurface minepool, metals largely are stable in the dissolved state (upper figure A).**
- **When mine waters are released to common river conditions (moderate pH and oxidizing), Fe, Al and Mn generally nucleate and precipitate to form amorphous or short-ranged ordered oxide minerals in colloidal form (e.g., ferrihydrite, gibbsite, birnessite) that are prominent in AMD releases as "yellowboy," (B)**
- **These solids slowly recrystallize to more stable crystalline phases (e.g., hematite, goethite, and ordered gibbsite and birnessite).**

Key Definitions:

- **Dissolved metals** – metal ions that are part of the liquid solution.
- **Colloidal and particulate metals** – small particles including metals, which are dispersed in a liquid solution, e.g. milk or paint

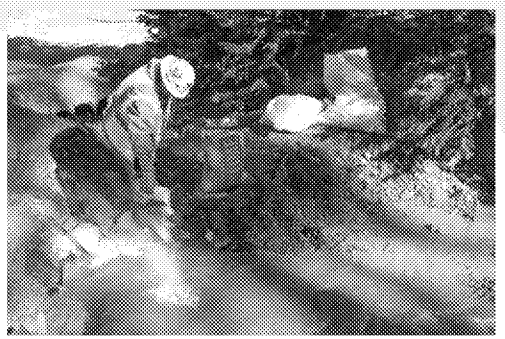


Geochemistry of the GKM Plume

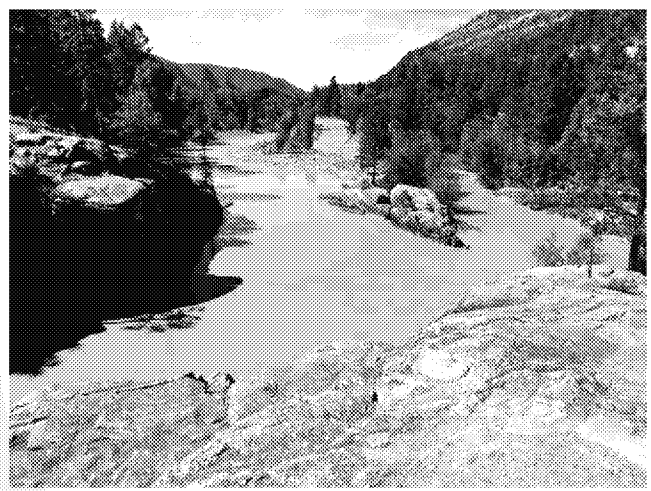
Animas River:

Substantive remedial action happens in the Animas

- Well buffered moderately alkaline pH
- Kinetics of oxidation vastly enhanced
- Major solute concentrations suppressed by hydroxide mineral precipitation
- Fast reaction rates favor amorphous to short-range ordered, colloidal-sized particle formation
- Charged colloidal surfaces foster continued suspension
- Minor solute concentrations suppressed by partitioning to incipient hydroxide colloids



The same processes used to treat acid mine drainage naturally occurred as the GKM plume travelled through the Animas River



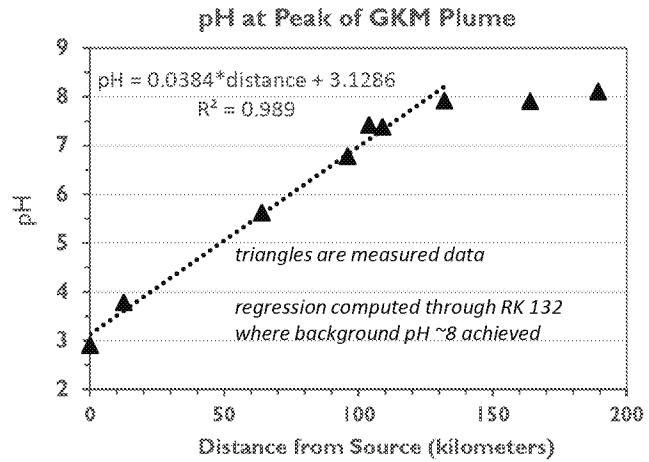
- **The river's yellow color signaled the occurrence of oxidation and acid neutralization**
- **Metals transformed from dissolved to colloidal/particulate form**

Abiotic Fe^{2+} oxidation half-life at P_{O2} = 0.2 atm.

pH (su)	$T_{1/2}$
0	65.89 years
1	65.89 years
2	65.64 years
3	61.01 years
4	7.32 years
5	30.05 days
6	7.22 hours
7	4.33 minutes
8	2.60 seconds
9	0.03 seconds

- Cement Creek is too acidic (2-4pH) for oxides to form as plume travelled
- Fe^{2+} in the release waters likely oxidized to Fe^{3+} quickly once the plume reached the Animas River where pH is 6-8

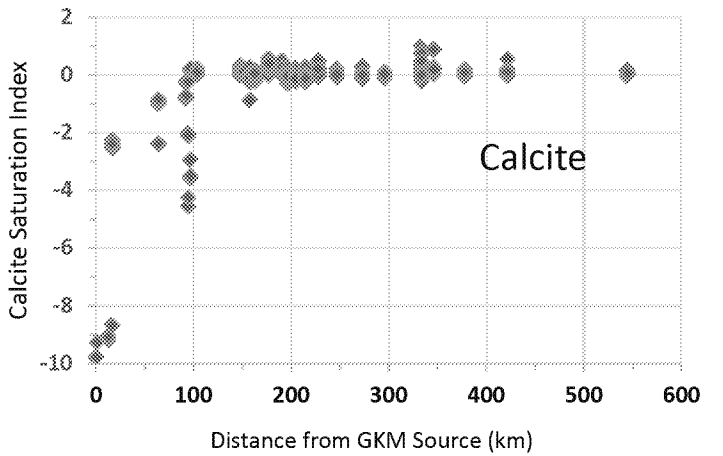
Geochemistry of GKM Plume

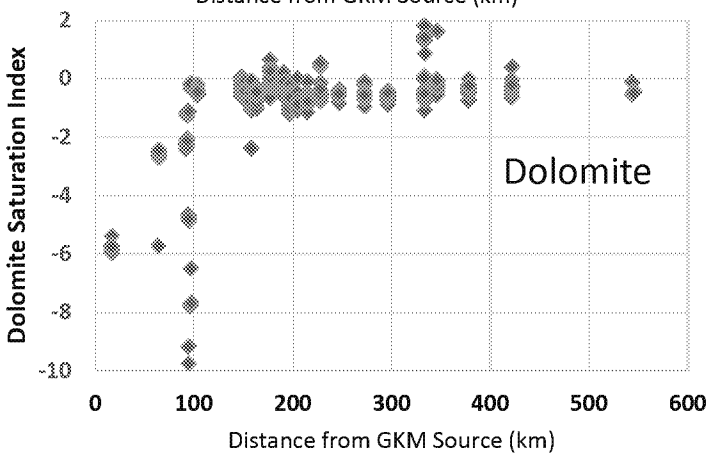


- pH increased linearly as the plume travelled downriver, generally reaching river baseline of approximately 8.0 at about RK 132 (NAR 06 sonde)
- Geochemical calculations based on pH suggest saturation with mineral phase such as calcite should be largely complete by ~ 100 km

SI=0 indicates saturation with mineral phase
Negative SI indicates water is undersaturated with the mineral

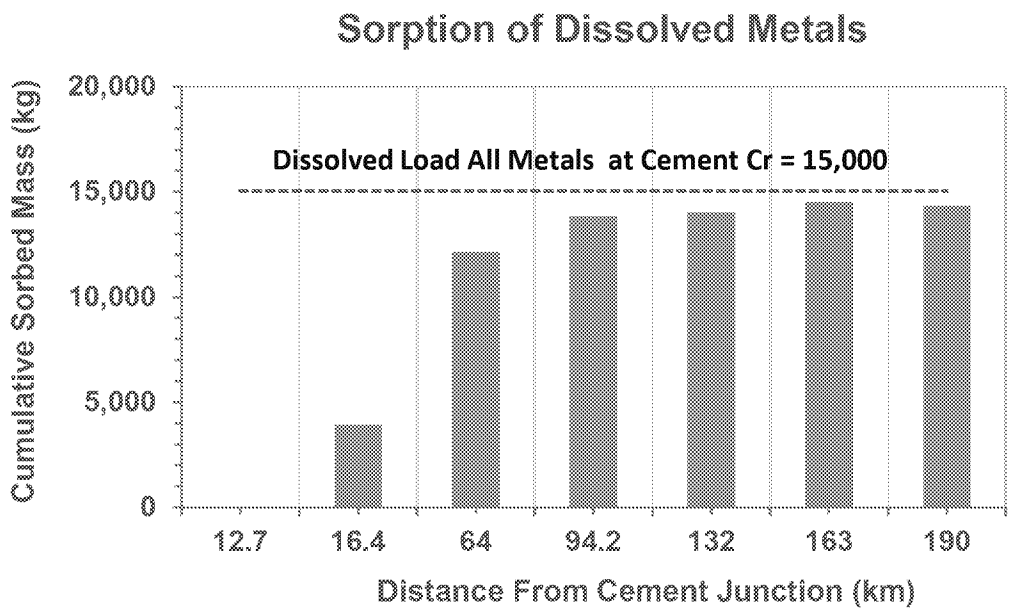
Saturation indices (SIs) for calcite and dolomite with distance from Gold King Mine

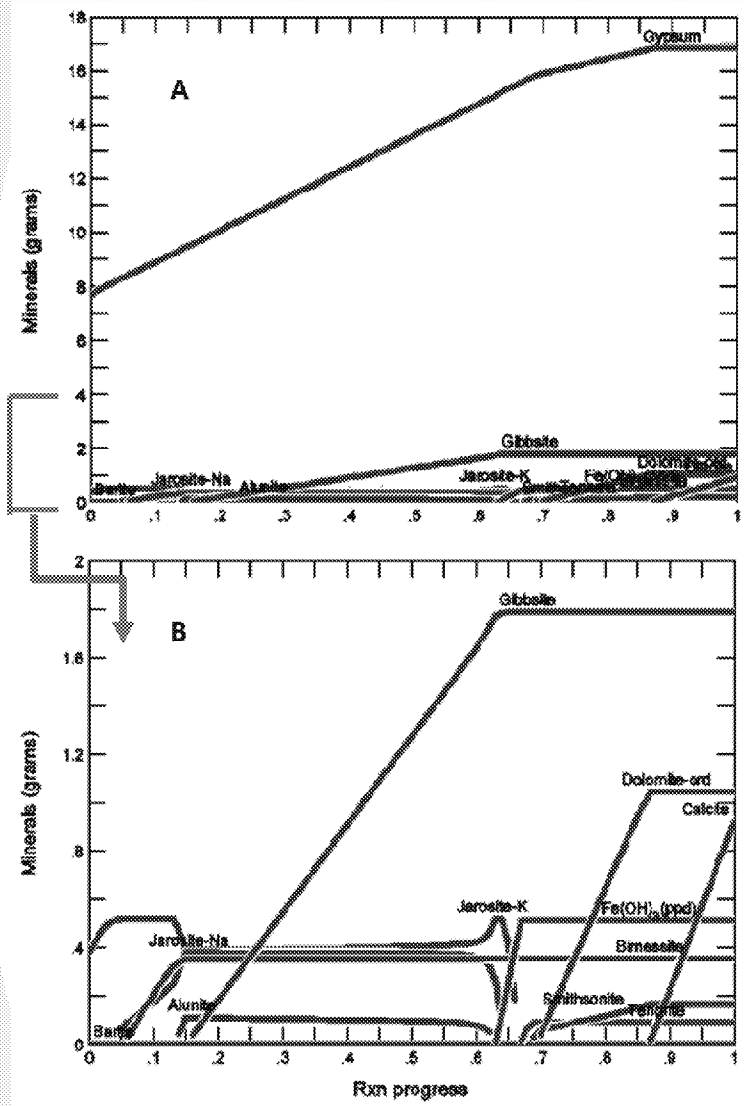




Geochemical Transformations

- Samples collected close to peak show that dissolved mass transitioned to particulate/colloidal mass as the plume travelled down river
- Longitudinal pattern was consistent with the geochemical predictions
- Dissolved mass that entered the Animas River at Cement Creek was 90% sorbed to particulate/colloidal phase by the time the plume reached Durango and completely sorbed at the Southern Ute Indian Tribe sampling site at river kilometer 132





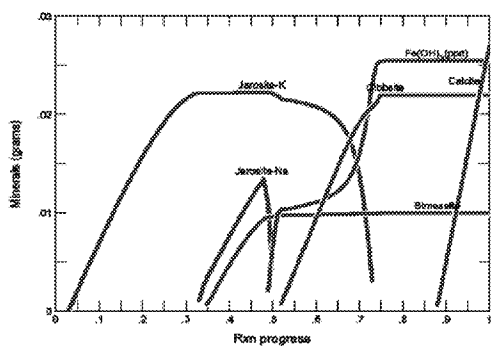
Mineralization Reactions Within GKM Plume

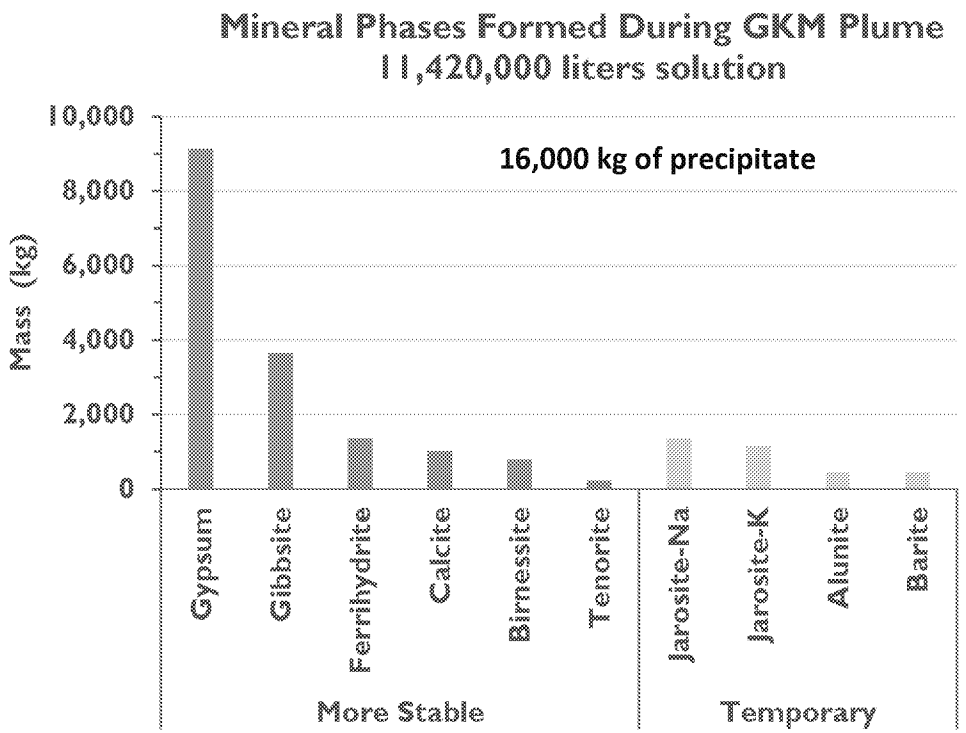
Simulated assuming a mass of calcite ($CaCO_3$) such that 1 kg of peak concentration release water is just barely saturated with calcite limestone at reaction's end consistent with Animas chemistry at 150 km (Geochemist's Workbench)

- Gypsum ($CaSO_4$) is supersaturated initially at low pH.
- Jarosite, alunite, and barite would have occurred in temporary phases
- Any of the temporary phases likely would have entrained trace metals within the lattice
- As the temporary phases re-dissolved the trace metals would re-enter solution.
- These trace metals would then be scavenged by the hydroxide minerals and then migrated down the Animas River
- At reactions end, gibbsite, ferrihydrite, birnessite, gypsum and dolomite precipitate from solution

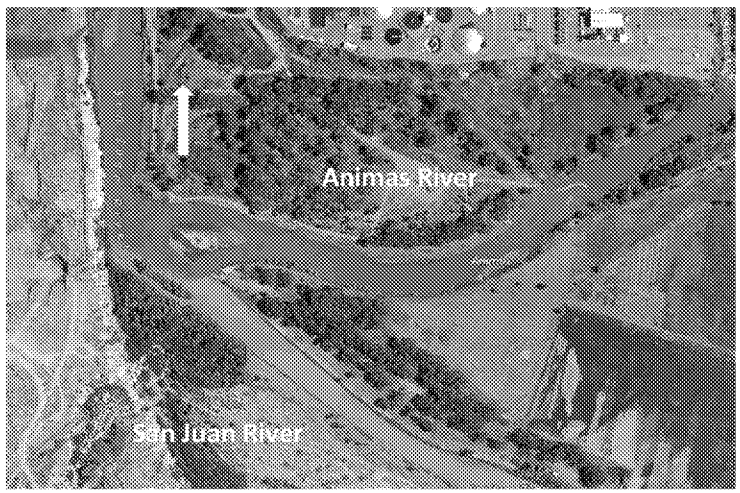
Mineralization Reactions

- The mass of minerals precipitated from the GKM plume can be calculated from the mass per 1 kg of solution shown in the reaction path multiplied by 11,420,000 kg of solution mass in the GKM release
- Approximately 16,000 kg of precipitate would have finally formed into gypsum, gibbsite, and ferrihydrite ($Fe(OH)_{3)}$ primarily
- Saturation with gypsum likely was relatively short-lived, and any that precipitated would have re-dissolved

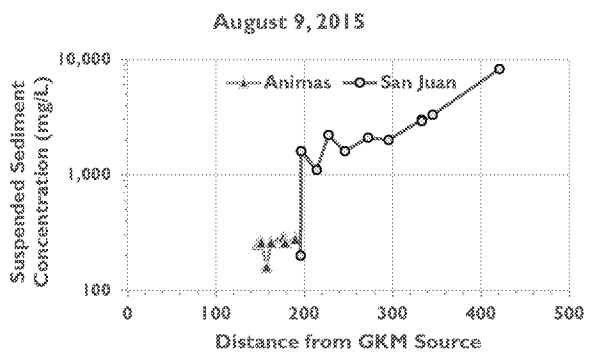




GKM Plume In the San Juan River

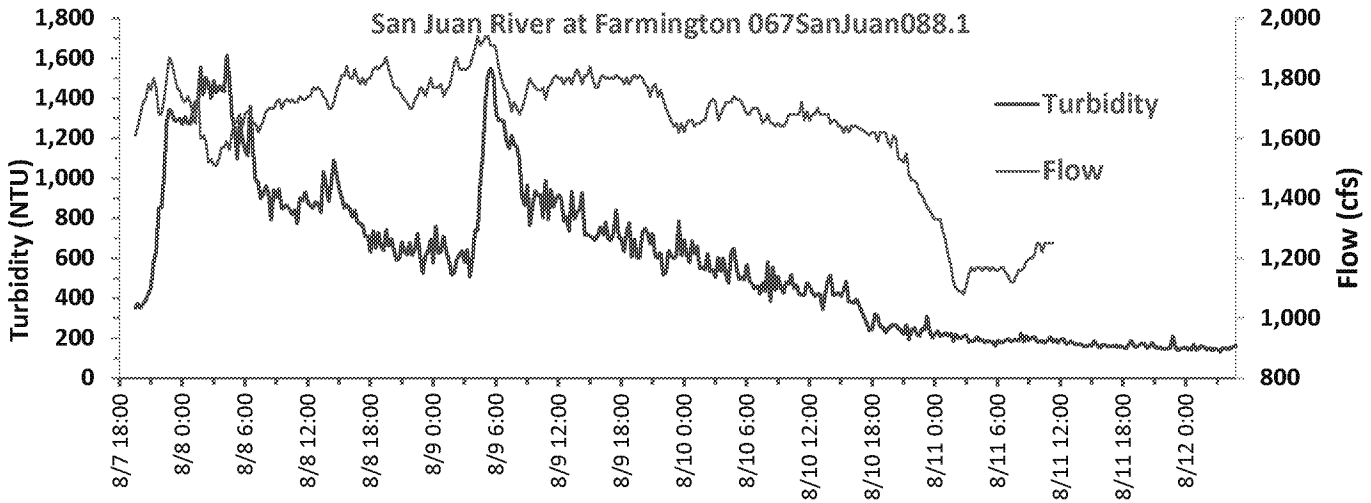


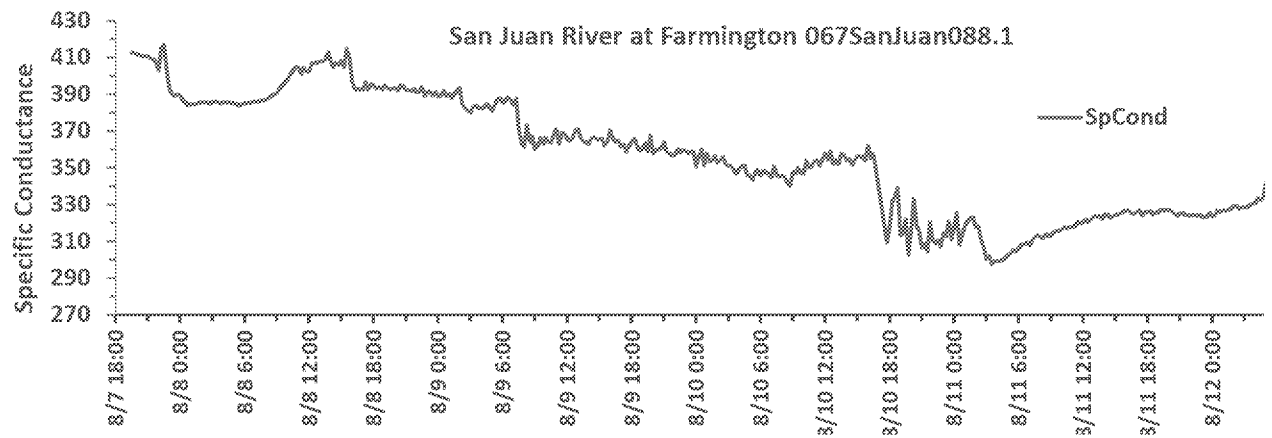
- **Plume readily visible in upper reach of San Juan**
- **No dissolved metals from GKM plume**
- **Massive influx of sediment from upstream San Juan**
- **Continually gained sediment downstream**



There was a lot of water in the rivers due to Navajo Dam release feeding the San Juan River and shut down of water withdrawals in the Animas River

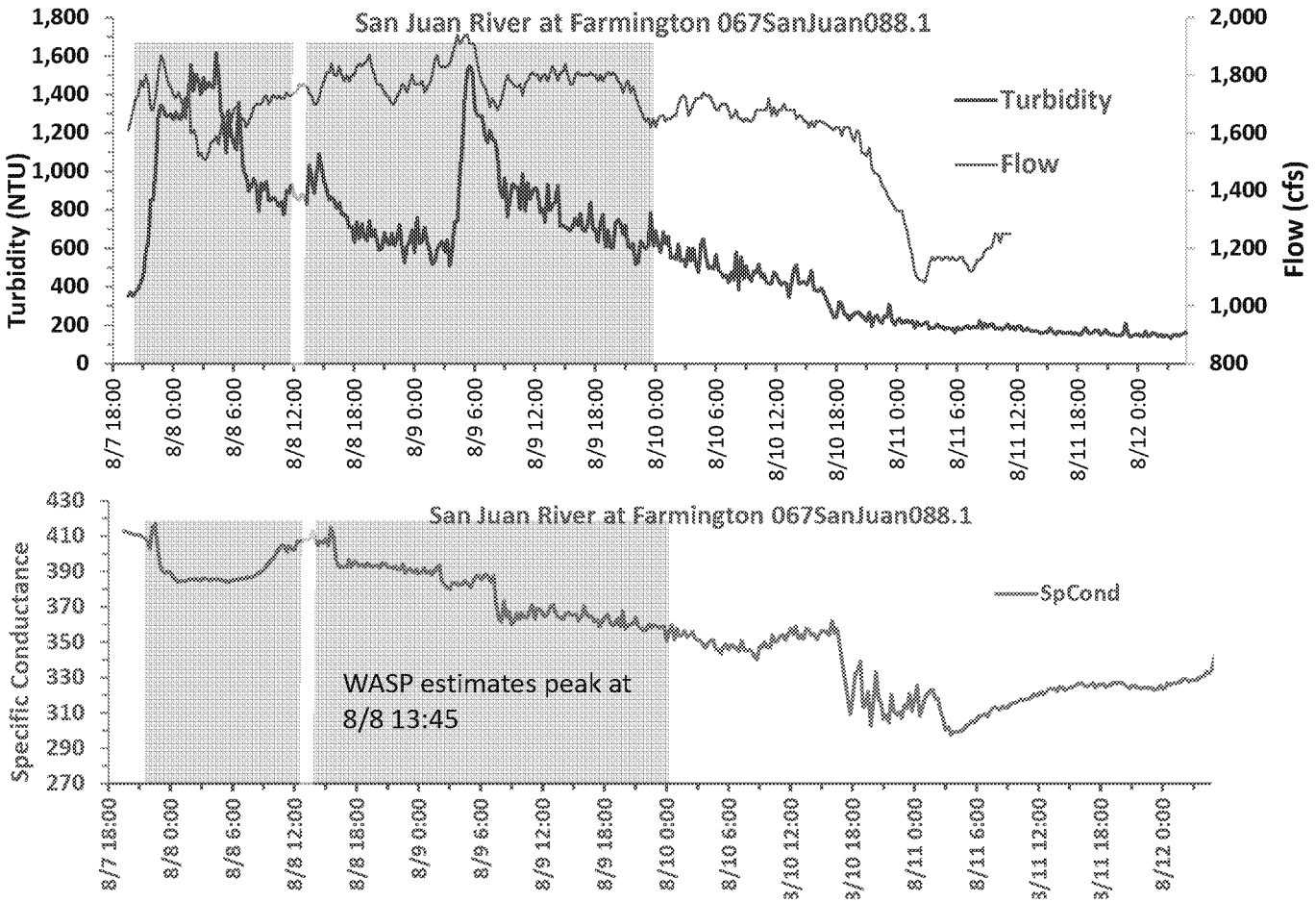
Sondes as Monitoring Devices in the San Juan River





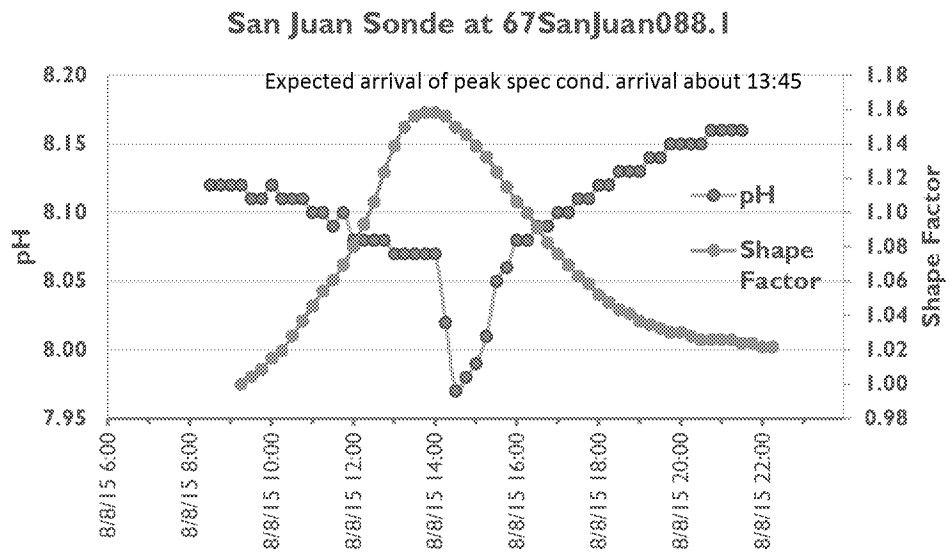
- There was a lot going on in the San Juan during GKM plume passage
- Increased flow from Navajo Dam
- High sediment concentrations and turbidity
- Where is the plume?

Sondes as Monitoring Devices in the San Juan River

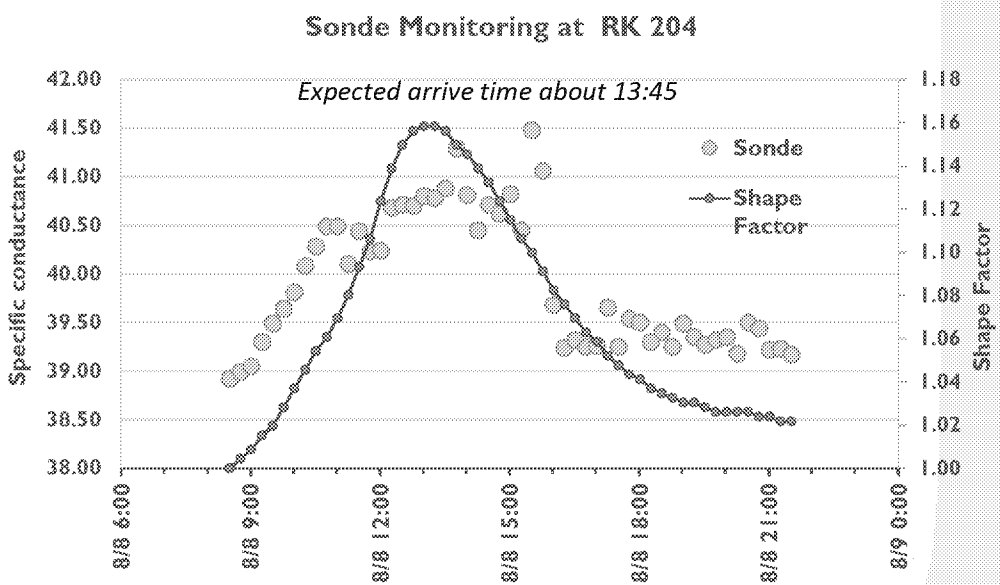


Observing the plume in the San Juan River at Farmington

NM 67SanJua088.1 at RK 204.4



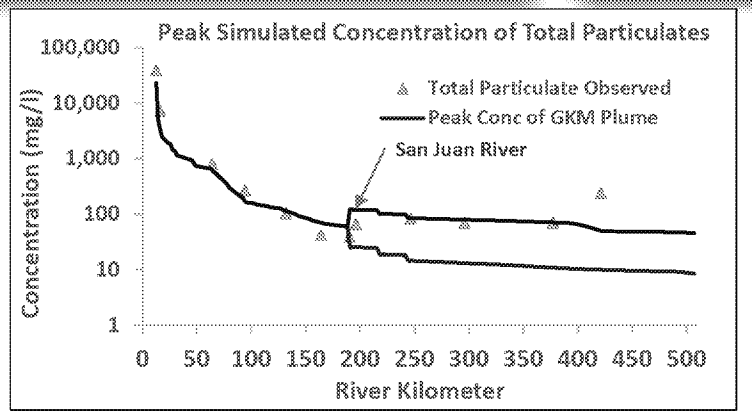
- **GKM mine plume could be detected in Sonde data because we knew when to look**
- **Values in GKM plume within range observed during higher flows**

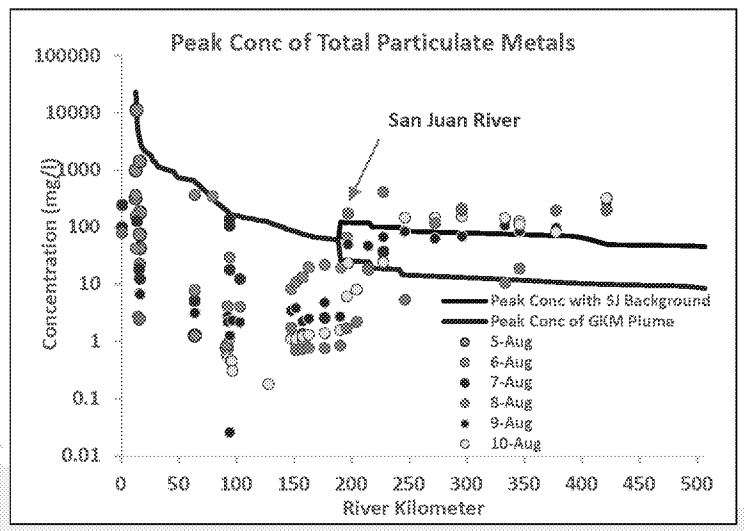


In comparing 5 available sondes, we note that parameters tended to peak at different times as the plume passed:

Specific Conductance < pH < Turbidity
+1 hr +2 hrs

Simulations: Total Particulates

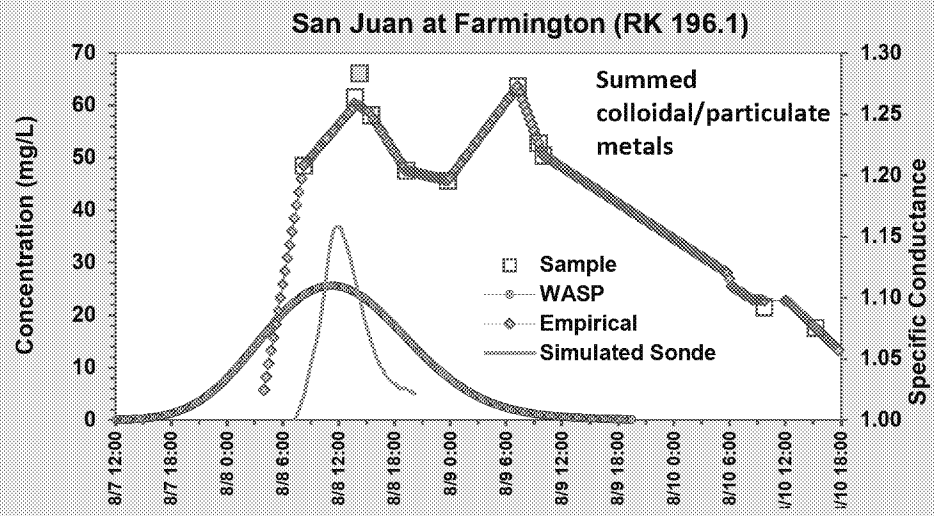


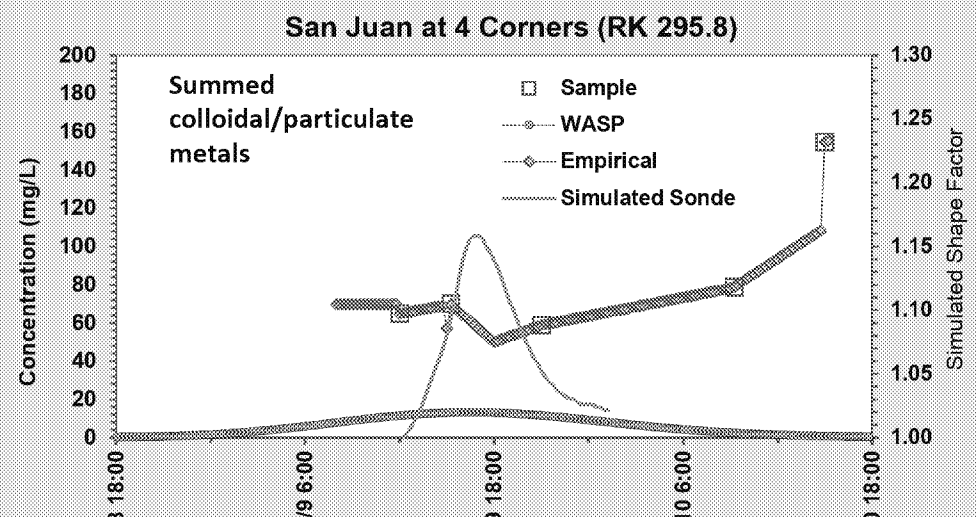


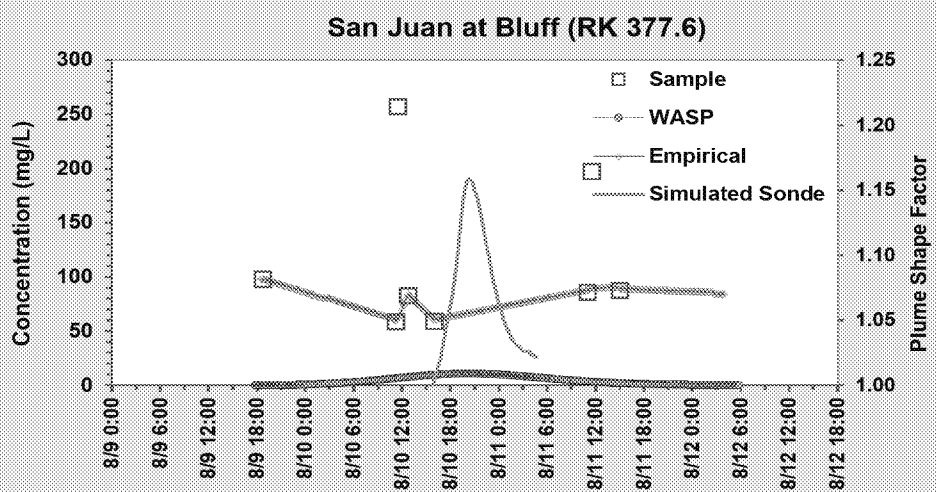
- **Two cases simulated for total particulate metal concentrations:**
  - **One solely due to the GKM release (red line)**
  - **One incorporating the incoming total particulate metals from the San Juan River upstream of the Animas River (black line)**
- **Top figure: empirically-estimated Peak Concentrations**
- **Bottom figure: measured concentrations by date and location**
- **Model suggests San Juan upstream metal concentrations account for rise in concentrations in the San Juan River**

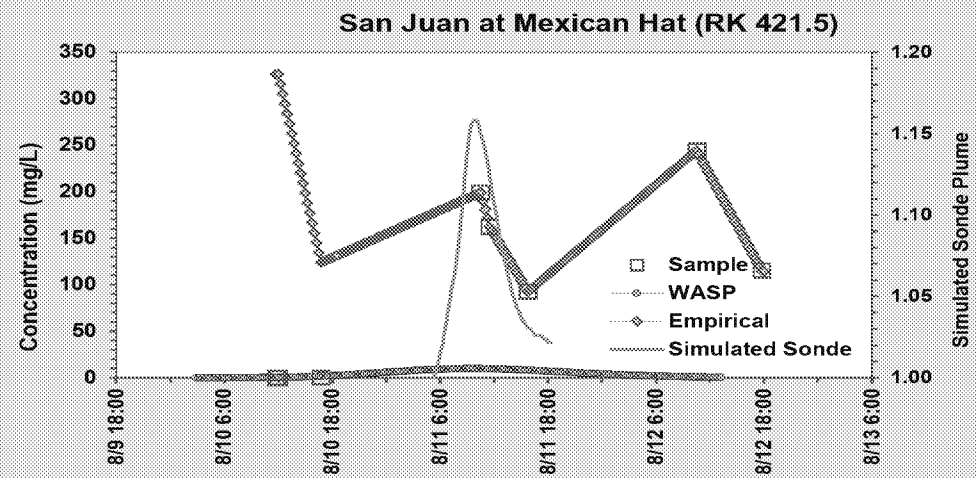
"As if flowing into distilled water"

Modeled Plumes in the San Juan





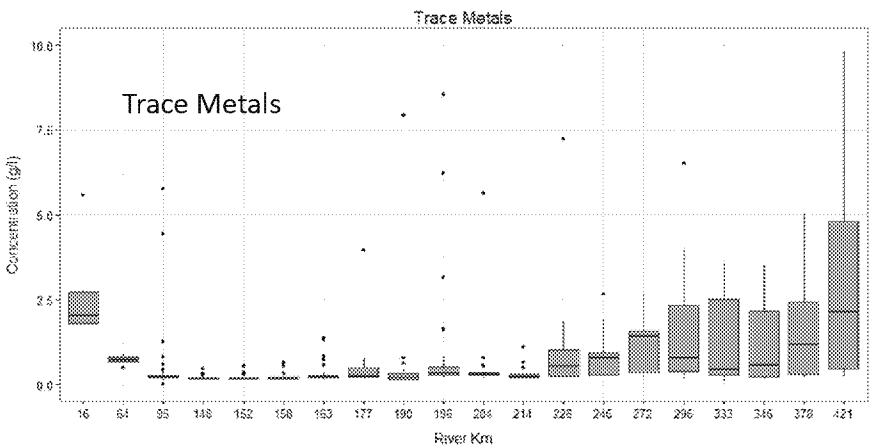




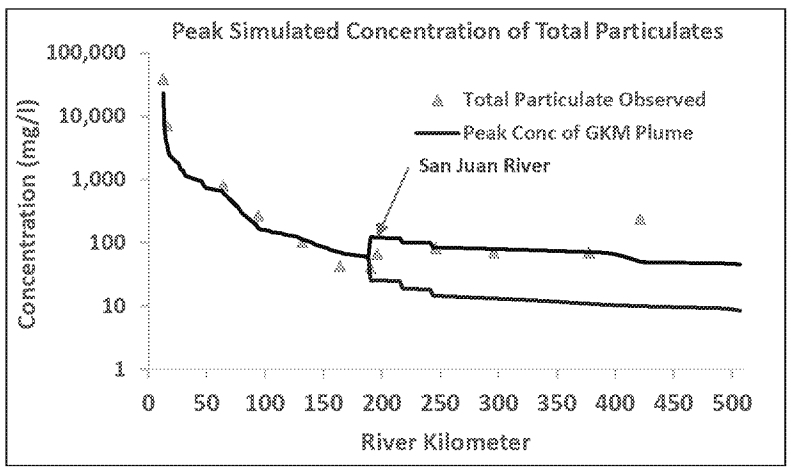
Metal Concentrations Observations

We could not detect the colloidal mass in the GKM plume after about Ship Rock, New Mexico

August measurements, including storms



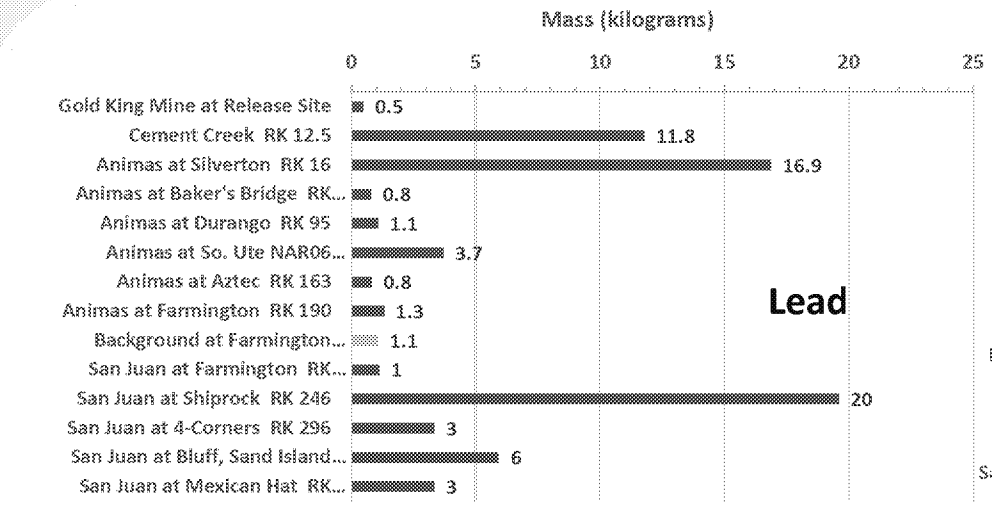
GKM Plume

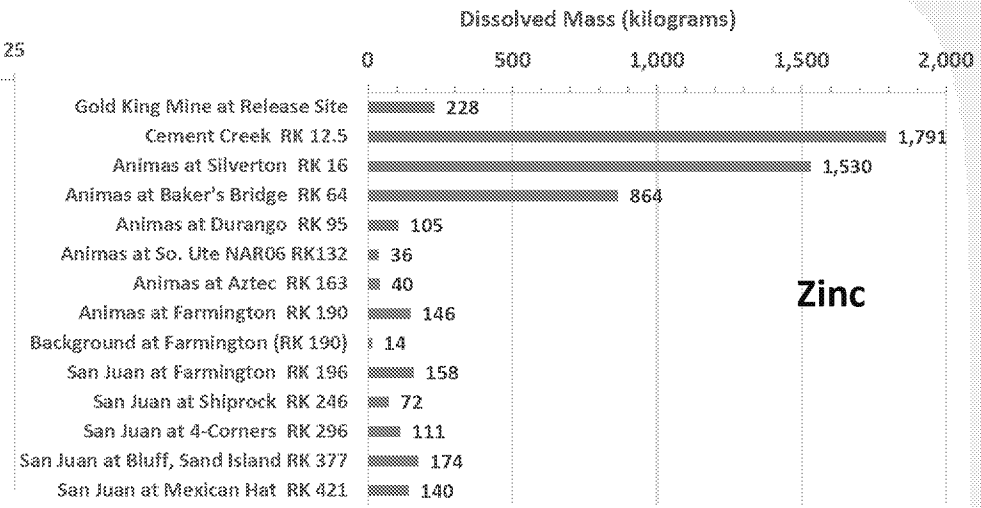


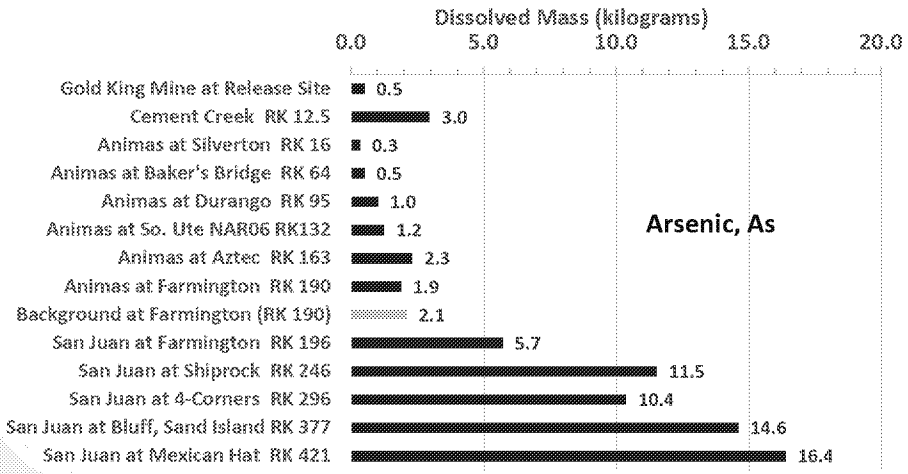
- **Water concentrations of metals in the San Juan tend to increase as it flows westward, especially increasing near Bluff and Mexican Hat, Utah** and during storms with sediment increases

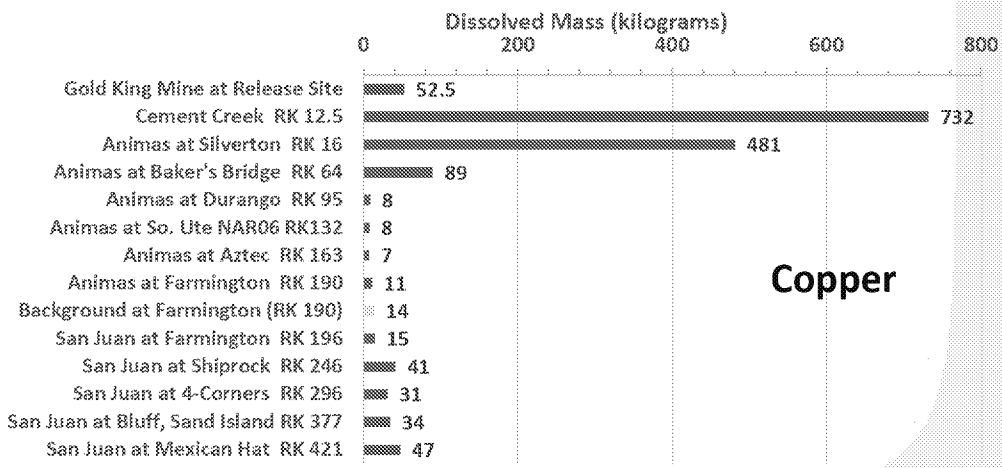
Sources of metals unknown in this study

Dissolved Mass Transport in GKM Plume (kg)



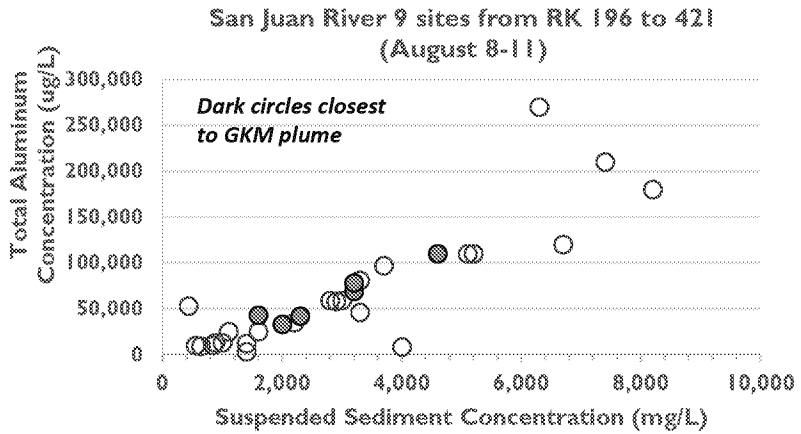


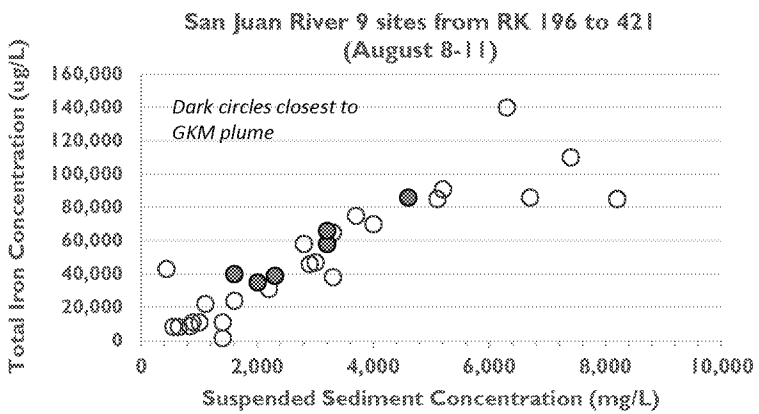




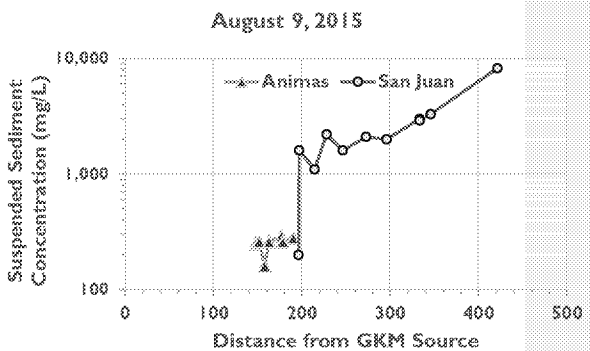
Searching for Parameters that Correlate with Metals

- **Low GKM sourced metal concentrations and silty water made tracking GKM plume in San Juan difficult**
- **Interest in correlating metals with suspended sediment or turbidity**
- **Not many sediment measurements during or after GKM plume or in historic data**
- **Looked into correlating with metals that correlate with sediment**
  - **Aluminum**
  - **Iron**



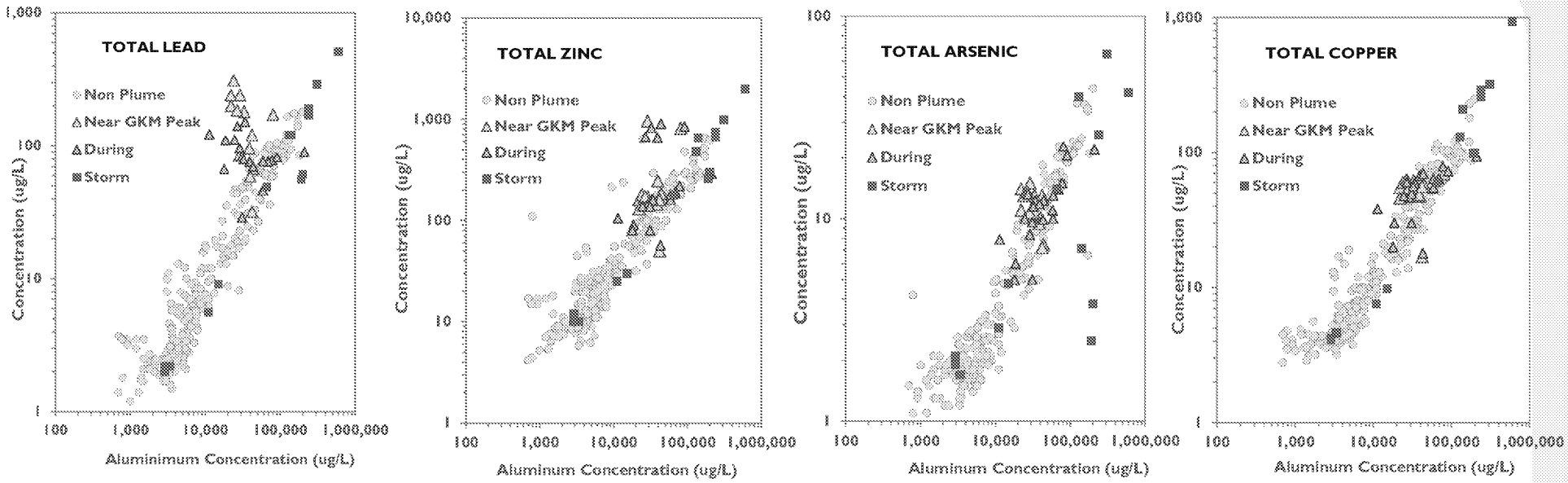


Sediments were elevated during the GKM plume period



Metals Concentrations in Relation to Aluminum Concentration in the San Juan River

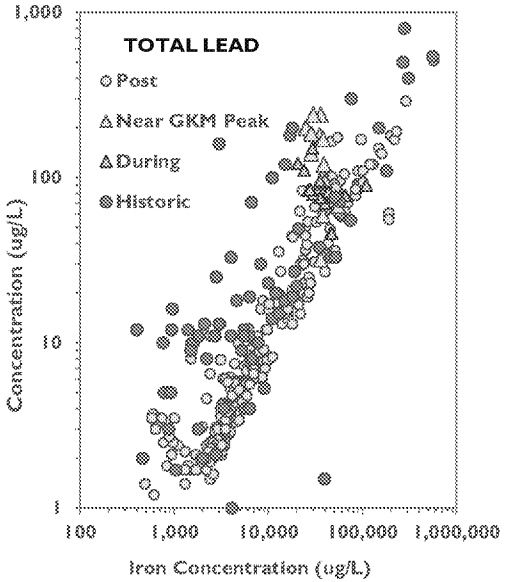
TOTAL FRACTION August to October 2015

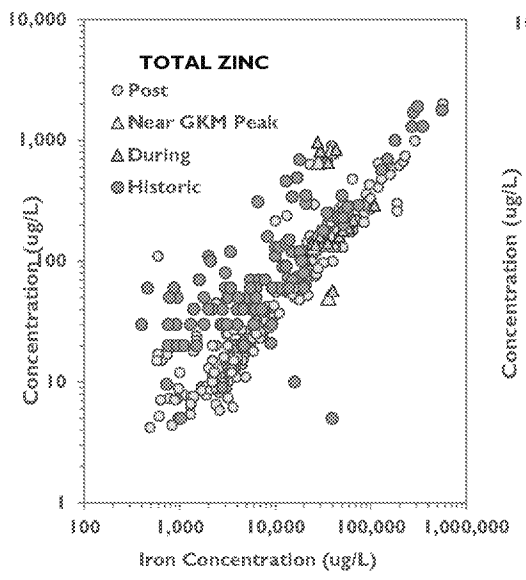


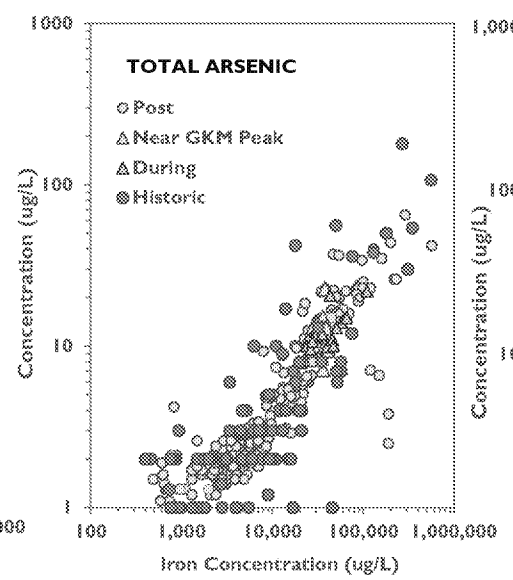
- There is a strong correlation of these metals with aluminum and iron (not shown)
- Isolating samples to expected GKM plume shows that the river was relatively "hot" for total lead and zinc compared to the usual relationship with aluminum. Most prevalent in samples from Farmington to Ship Rock—peaks from 4 Corners to Mexican Hat fade into background
- No elevated concentrations of arsenic and copper were evident.
- Post-GKM storms carried more metals than the plume: the Aug 28 storm produced relatively low concentrations while the Sep 26 event produced the highest observed values of aluminum and other metals

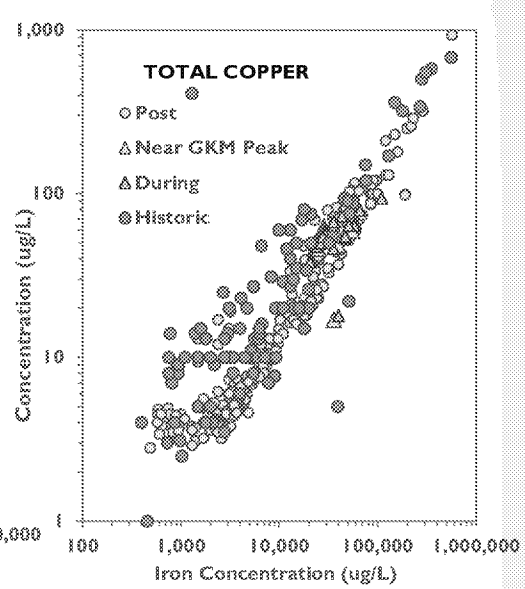
Metals Concentrations in Relation to Aluminum Concentration in the San Juan River

TOTAL FRACTION GKM Plume Period + USGS historic from gaging sites



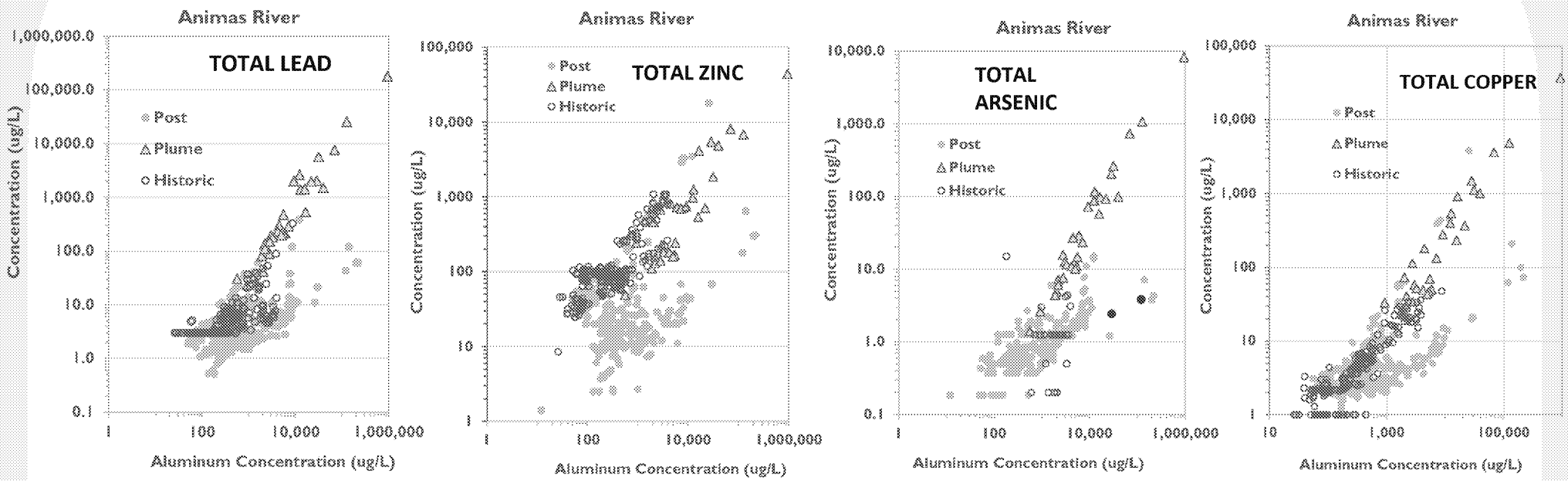






- **Relationship to iron is shown because USGS rarely reports aluminum (virtually identical to Fe)**
- **Post-plume data generally within the variability of historic data**

Metals Concentrations in Relation to Aluminum in the Animas River



- Relationships between metals and aluminum also holds in Animas River
- GKM plume produced concentrations of metals relative to aluminum that were largely unprecedented in historic data
- Post plume concentrations are generally lower

Exposure Potential to Metals from the Gold King Mine Plume

EPA/States/Tribes/Municipalities managed exposure during passage of the GKM plume by curtailing water use for domestic supply, recreation, irrigation and agriculture

What was the duration of potential exposure?

- **For aquatic life?**
- **If exposures had not been managed?**

Water Quality Screening Thresholds—Various Uses, Metals, Agencies

Surface Water in mg/L

	Screening Criteria		Aluminum	Antimony	Arsenic	Barium	Beryllium	Cadmium	Calcium	Chromium	Cobalt	Copper	Iron	Lead	Magnesium	Manganese	Mercury	Molybdenum	Nickel	Potassium	Selenium	Silver	Sodium	Thallium	Vanadium	Zinc
Drinking Water Related	Drinking water MCL	EPA (DWA)		0.006	0.010	2.000	0.004	0.005				1.300		0.015			0.002				0.050			0.002		
	Secondary Drinking	EPA (DWA)	0.050									1.000	0.300			0.050						0.100	30.000			5.000
	Child Health Advisory 1-Day	EPA (DWA)		0.010		0.700	30.000	0.040								1.000	0.002	0.080	1.000			0.200		0.007		6.000
	Domestic Supply	Colorado			0.01	1.0		0.005		0.05				0.05			0.002					0.1				
	Domestic Supply	New Mexico		0.006	0.010	2.000	0.004	0.005		0.100		1.300		0.015					0.700		0.050			0.002		10.500
	Domestic Source	Utah			0.010	1.000	0.004	0.010		0.05				0.015			0.002				0.050	0.050				
	Health Based Ingestion	Utah	5.25	6.75	31.25							7.75	11.75	37.25		7.0								40.5		
Recreation	Recreational	Region 8	170.000	0.067	0.050	33.000	0.330	0.083		220	0.050	6.700	120.000	0.200		7.800	0.050	0.830	3.300		0.830			0.002	0.830	50.000
Agricultural (Irrigation, livestock)	Irrigation	Region 6		5.000				0.010		0.100	1.000	0.200		5.000		0.200			0.200		0.130				0.100	2.000
	Irrigation	New Mexico	5.000		0.100			10.000		0.100	0.050	0.200		5.000				1.000			0.130				0.100	2.000
	Irrigation (short-term)	Utah	20.000		2.000			0.050		1.000	5.000	5.000	20.000	10.000		10.000		0.050			0.020				1.000	10.000
	Agriculture	Colorado			0.100							0.200	1.000													
	Agricultural Supply	Navajo Nation	5.000		0.100			0.010		0.100	0.050	0.200		5.000				0.010			0.130				0.100	2.000
	Revised Irrigation	Region 9	5.000		2.000			0.050		1.000	0.050	0.200		10.000				1.000			0.020				0.100	10.000
	Livestock	Region 6					0.100	0.050		1.000		0.500		0.100			0.010		1.000		0.250				0.100	25.000
	Livestock updated	Region 9			0.200			0.050		1.000	1.000	0.500		0.100							0.050				0.100	25.000
	Livestock	New Mexico			0.200			0.050		1.000	1.000	0.500		0.100							0.050				0.100	25.000
	Livestock	Utah	5.000		0.200			0.050	500.0	1.000	1.000	0.500		0.100	250.0		0.010				0.050		1000.0		0.100	25.000
	Livestock and Wildlife Watering	Navajo Nation	0.500		0.020	10.000		0.050		1.000	1.000	0.500		0.100			0.01				0.002				0.100	25.000
Aquatic Life	Water + Fish	Colorado		0.006	0.00002					100.000		1.300							0.610		0.170			0.00024		7.400
	Aquatic Acute	Navajo Nation	0.750	0.088	0.340		0.065	0.008		0.012		0.021		0.038			0.0024		0.761		0.002	0.007		0.700		0.176
	Aquatic Acute	Region 6		8.358	0.340			0.003		0.372		0.025		0.130		3.710	0.001		0.813		0.020	0.010				0.290
	Aquatic Acute	Region 9	8.358				0.340	0.003		0.372		0.025		0.130		3.710	0.104		0.813		0.020	0.010				0.290
	Aquatic Acute	Colorado	7.650		0.340			0.003		0.016		0.024		0.136		3.697			0.806		0.0184	0.007				0.2960
	Aquatic Acute	New Mexico	7.650		0.340			0.003		0.004		0.0250		0.026		3.882		7.92	0.900		0.020	0.008				0.288
	Aquatic Acute	Utah	0.750		0.340			0.002		0.570		0.0130	1.000	0.065					0.468		0.0184	0.0016				0.120
	Warm Water Fish 1-hr	Utah	0.750		0.340			0.002		0.570		0.0130	1.000	0.065					0.468		0.0184	0.0016				0.120
	Warm Water Fish 4-day	Utah	0.087		0.150			0.0009		0.074		0.0090	1.000	0.0025					0.052		0.0046					0.120
	Aquatic Chronic	Utah	0.087					0.0009		0.074		0.0090	1.000	0.0025			0.00001		0.052		0.0046					0.120
	Aquatic Chronic	Region 6		3.348	0.150			0.00072		0.126	0.050	0.016		0.005		2.050	0.001		0.050		0.005					0.213
	Aquatic Chronic	Region 9	3.348				0.150	0.001		0.126		0.016		0.005		2.050	0.001		0.050		0.005					0.213
	Aquatic Chronic	Colorado	1.262		0.150			0.0007		0.011		0.0162	1.000	0.0053		2.042	0.00001	0.160	0.050		0.0046	0.00023		0.015		0.228
	Aquatic Chronic	Navajo Nation	0.087	0.030	0.150		0.005	0.0004		0.070		0.0138		0.039			0.000012		0.085		0.002			0.150		0.183
	Aquatic Chronic	New Mexico	1.365		0.150			0.0010		0.069		0.016		0.003		2.145	0.001	1.895	0.100		0.005					0.230

Blue shading is dissolved ***Yellow shading is total***

Hardness-based criteria calculated at 180 mg/l

Application of water quality criteria

- **What criteria?**
  - Selected criteria in each major use category using primarily state criteria
  - Appropriate state criteria were applied to each site depending on its location
  - Applied reach specific criteria relative to beneficial use designation in upper Animas in Colorado
  - Navajo Nation criteria for sites in the San Juan shown separately
- **How applied?**
  - GKM plume empirically-reconstructed plume at each of the 12 sites was screened against criteria
  - The number of time periods where estimated concentrations were equal to or greater than the criteria were counted and converted to hours
  - Both dissolved and total criteria were applied
  - Tables that follow show total or dissolved hours for each beneficial use. (Usually, one or the other fraction is used for a beneficial use—not both)

GKM Plume Concentrations Relative to Water Quality Criteria

Aquatic --Acute

Hours at or above criteria during passage of the GKM plume

	Animas River							San Juan River				
	Cement Creek (RK 12.5)	Silverton (RK 16.4)	Bakers Bridge (RK 64)	Durango (RK 94.2	SUIT NAR06 RK 132	Aztec (RK 162.9	Farmington (RK 190.2)	Farmington (RK196)	Ship Rock (RK 246.3)	4 Corners (RK 295.8)	Bluff (RK 377.6)	Mexican Hat (RK 421.5)
Aluminum	0.00	8.50	10.25	6.25	6.00	0.50	0.50	48.25	48.25	22.75	45.50	49.50
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Barium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Beryllium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cadmium	0.00	9.75	7.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
calcium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chromium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cobalt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper	0.00	9.75	12.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.00	0.00	0.00
Lead	0.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
magnesium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molybedenum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nickel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
potassium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Selenium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silver	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thallium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc	0.00	13.75	12.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Source	*CO* Not Designated	*CO*	*CO*	*CO*	*CO*	*NM*	*NM*	*NM*	*NM*	*Utah*	*Utah*	*Utah*

Note:
Color coding is not meaningful to application of wq criteria.

Colors were chosen by EXCEL to separate relative differences within range represented in each table.

GKM Plume Concentrations Relative to Water Quality Criteria

Aquatic Chronic

Hours at or above criteria during passage of the GKM plume

	Animas River							San Juan River				
	Cement Creek (RK 12.5)	Silverton (RK 16.4)	Bakers Bridge (RK 64)	Durango (RK 94.2	SUIT NAR06 RK 132	Aztec (RK 162.9	Farmington (RK 190.2)	Farmington (RK196)	Ship Rock (RK 246.3)	4 Corners (RK 295.8)	Bluff (RK 377.6)	Mexican Hat (RK 421.5)
Aluminum	0.00	13.75	18.75	33.50	43.25	17.25	17.25	48.25	48.25	22.75	45.50	34.00
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Barium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Beryllium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cadmium	0.00	13.75	12.25	5.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
calcium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chromium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cobalt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper	0.00	9.75	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron	0.00	13.75	40.00	37.25	44.00	0.00	0.00	0.00	0.00	6.00	0.00	0.00
Lead	0.00	6.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
magnesium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese	0.00	6.25	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molybedenum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nickel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
potassium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Selenium	0.00	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silver	0.00	13.75	12.00	20.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thallium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc	0.00	13.75	13.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Source	***CO***	***CO***	***CO***	***CO***	***CO***	***NM***	***NM***	***NM***	***NM***	***Utah***	***Utah***	***Utah***
	Not Designated											

Note:
Color coding is not meaningful to application of wq criteria.

Colors were chosen by EXCEL to separate relative differences within range represented in each table.

GKM Plume Concentrations Relative to Water Quality Criteria

Domestic Supply

Hours at or above criteria during passage of the GKM plume

	Animas River							San Juan River				
	Cement Creek (RK 12.5)	Silverton (RK 16.4)	Bakers Bridge (RK 64)	Durango (RK 94.2	SUIT NAR06 RK 132	Aztec (RK 162.9	Farmington (RK 190.2)	Farmington (RK196)	Ship Rock (RK 246.3)	4 Corners (RK 295.8)	Bluff (RK 377.6)	Mexican Hat (RK 421.5)
Aluminum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	48.25	48.25	48.25
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	0.00	0.00	18.25	13.75	19.25	0.00	0.00	0.00	0.00	48.25	48.25	48.25
Barium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.50
Beryllium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cadmium	0.00	0.00	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
calcium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chromium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.50
Cobalt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.50	0.50	0.50
Iron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	48.25	48.25	48.25
Lead	0.00	0.00	36.25	34.50	35.50	0.00	0.00	0.00	0.00	48.25	48.25	48.25
magnesium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	48.25	48.25	48.25
Molybedenum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nickel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
potassium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Selenium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silver	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thallium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	48.25	48.25	48.25
Vanadium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.25	0.50	29.50
Zinc	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Source	***CO***	***CO***	***CO***	***CO***	***CO***	***NM***	***NM***	***NM***	***NM***	***Utah***	***Utah***	***Utah***
	Not Designated									**Health Based Ingestion Drinking Water**		

Note:
Color coding is not meaningful to application of wq criteria.

Colors were chosen by EXCEL to separate relative differences within range represented in each table.

GKM Plume Concentrations Relative to Water Quality Criteria

Recreation

Hours at or above criteria during passage of the GKM plume

	Animas River							San Juan River				
	Cement Creek (RK 12.5)	Silverton (RK 16.4)	Bakers Bridge (RK 64)	Durango (RK 94.2	SUIT NAR06 RK 132	Aztec (RK 162.9	Farmington (RK 190.2)	Farmington (RK196)	Ship Rock (RK 246.3)	4 Corners (RK 295.8)	Bluff (RK 377.6)	Mexican Hat (RK 421.5)
Aluminum	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Barium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Beryllium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cadmium	4.25	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
calcium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chromium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cobalt	7.75	2.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper	5.00	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lead	17.75	5.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
magnesium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese	11.50	2.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molybedenum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nickel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
potassium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Selenium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silver	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thallium	4.75	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Source	***EPA Region 8***											

Note:
Color coding is not meaningful to application of wq criteria.

Colors were chosen by EXCEL to separate relative differences within range represented in each table.

GKM Plume Concentrations Relative to Water Quality Criteria

Agriculture

Hours at or above criteria during passage of the GKM plume

	Animas River					San Juan River						
	Cement Creek (RK 12.5)	Silverton (RK 16.4)	Bakers Bridge (RK 64)	Durango (RK 94.2	SUIT NAR06 RK 132	Aztec (RK 162.9	Farmington (RK 190.2)	Farmington (RK196)	Ship Rock (RK 246.3)	4 Corners (RK 295.8)	Bluff (RK 377.6)	Mexican Hat (RK 421.5)
Aluminum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	17.25	7.00	8.50	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Barium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Beryllium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cadmium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
calcium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chromium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cobalt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper	17.75	9.75	11.25	5.50	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron	17.75	13.75	40.00	37.25	44.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lead	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
magnesium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molybedenum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nickel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
potassium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Selenium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silver	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thallium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Source	***CO***	***CO***	***CO***	***CO***	***CO***	***NM***	***NM***	***NM***	***NM***	***Utah***	***Utah***	***Utah***

Note:
Color coding is not meaningful to application of wq criteria.

Colors were chosen by EXCEL to separate relative differences within range represented in each figure.

GKM Plume Concentrations Relative to Water Quality Criteria

Livestock

Hours at or above criteria during passage of the GKM plume

	Animas River							San Juan River				
	Cement Creek (RK 12.5)	Silverton (RK 16.4)	Bakers Bridge (RK 64)	Durango (RK 94.2	SUIT NAR06 RK 132	Aztec (RK 162.9	Farmington (RK 190.2)	Farmington (RK196)	Ship Rock (RK 246.3)	4 Corners (RK 295.8)	Bluff (RK 377.6)	Mexican Hat (RK 421.5)
Aluminum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Barium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Beryllium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cadmium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
calcium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chromium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cobalt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lead	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
magnesium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molybedenum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nickel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
potassium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Selenium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silver	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thallium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Source	*CO*	*CO*	*CO*	*CO*	*CO*	*NM*	*NM*	*NM*	*NM*	*Utah*	*Utah*	*Utah*

Note:
Color coding is not meaningful to application of wq criteria.

Colors were chosen by EXCEL to separate relative differences within range represented in each table.

GKM Plume Concentrations Relative to Water Quality Criteria

Navajo Nation — San Juan River

Hours at or above criteria during passage of the GKM plume

Criteria	Location	Aluminum	Antimony	Arsenic	Barium	Beryllium	Cadmium	Calcium	Chromium	Cobalt	Copper	Iron	Lead	Magnesium	Manganese	Molybdenum	Nickel	Potassium	Selenium	Silver	Sodium	Thallium	Vanadium	Zinc
Agricultural Supply	Ship Rock	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4 Corners	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Bluff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mexican Hat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Livestock and Wildlife Watering	Ship Rock	48.25	0	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19.25	0	0	0	0	0
	4 Corners	48.25	0	7.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17.50	0	0	0	0	0
	Bluff	48.25	0	0.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.50	0	0	0	0	0
	Mexican Hat	48.25	0	34.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33.75	0	0	0	0	0
Aquatic Acute	Ship Rock	29.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19.25	0	0	0	0	0
	4 Corners	22.75	0	0	0	0	0	0	0	0	12.00	0	0	0	0	0	0	0	0	0	0	0	0	0
	Bluff	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.50	0	0	0	0	0
	Mexican Hat	49.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aquatic Chronic	Ship Rock	40.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19.25	0	0	0	0	0
	4 Corners	22.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17.50	0	0	0	0	0
	Bluff	45.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.50	0	0	0	0	0
	Mexican Hat	34.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33.75	0	0	0	0	0

Note:
Color coding is not meaningful to application of wq criteria.

Colors were chosen by EXCEL to separate relative differences within range represented in each table.

Exposure Observations

- **Acute Aquatic Criteria**
  - **Criteria for aluminum exceeded at all sites—mostly due to total criteria**
    - **0.5 hrs at Durango up to 8 hours at Silverton**
  - **Criteria for cadmium, copper, lead and zinc exceeded for up to 12 hours**
  - **Duration declined in downstream direction with general pattern of concentration**
  - **No exceedances in most metals anywhere in Animas and for any metal other than aluminum in Animas south of Durango**
- **Domestic supply/water ingestion criteria for a number of metals exceeded in Utah segment of San Juan during time of passage of GKM plume (due to health-based ingestion criteria based on total metals)**
- **Total aluminum is high in the San Juan River so that aquatic, Utah water ingestion criteria, and Navajo Nation criteria for this metal routinely exceeded. In the San Juan River, aluminum concentrations are related to flow**
- **Even during GKM plume passage, most criteria for most uses were not exceeded**

Summary of Key Findings

- Dissolved and total metals concentrations declined sharply from very high concentrations near the GKM source as the plume traveled in the downstream direction due to dilution, deposition, and geochemical transformations.
- The potential toxicity of the dissolved metals in the AMD was mitigated as high pH in the Animas River neutralized the acidity and precipitated metals as the plume traveled.
- Dissolved metals were at pre-release levels by the time the GKM plume entered the San Juan River. Metals concentrations generally increased in the San Juan River in the downstream direction.
- Concentrations retreated close to pre-event conditions within hours to days after the plume passed.
- Despite high metals concentrations, water quality criteria for most uses and metals were not exceeded.
  - Most exceedances in the upper Animas; few in the lower Animas.
  - Exceedances in the San Juan river occurred in lower reaches but not upper reaches, with most due to total aluminum